

Hammering Wear Impact Fatigue Hypothesis WEC/irWEA failure mode on roller bearings

Presented by Johan Luyckx
Manager Product Integrity Management
Hansen Transmissions International nv
Kontich Belgium

Research results

- ↪ Hansen communication policy is to release the WEC/irWEA research results in an early stage:
 - stimulate other researchers
 - support maximal the wind industry for gearbox reliability increase

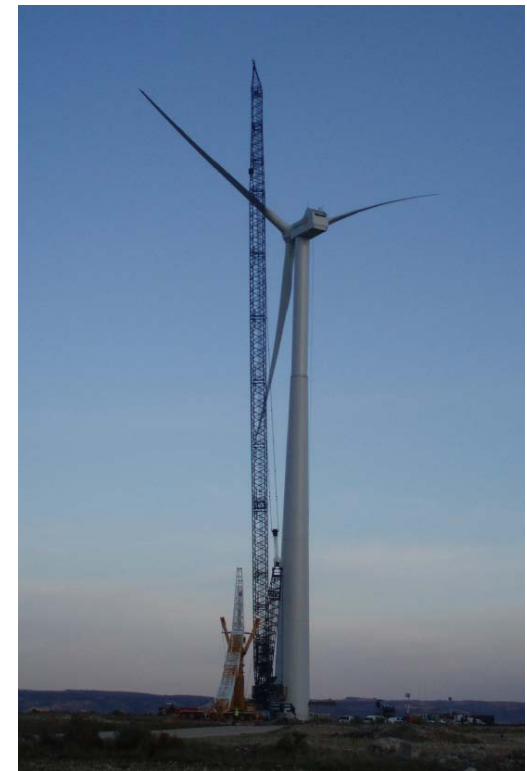
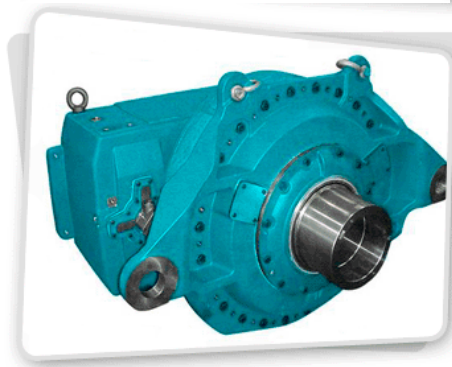
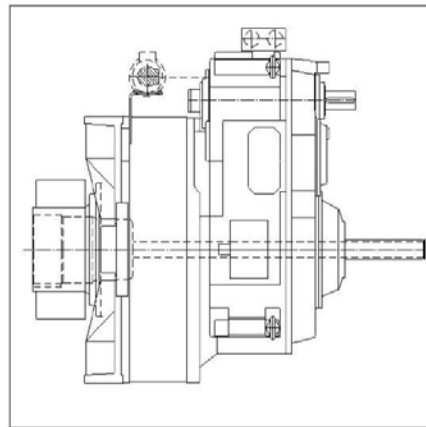
- ↪ This presentation is based on the actual status of research data and can be reviewed.

Agenda

- 1. Introduction
- 2. Material observations in WEC/irWEA failed bearings
- 3. Interpretation of material observations
- 4. Hansen wind experience
- 5. Hypothesis development & Material research
- 6. Proposals for WEC/irWEA research
- 7. Summary and way forward

1. Introduction

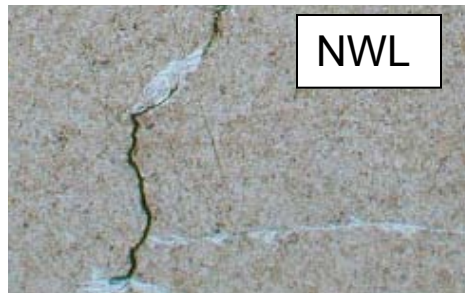
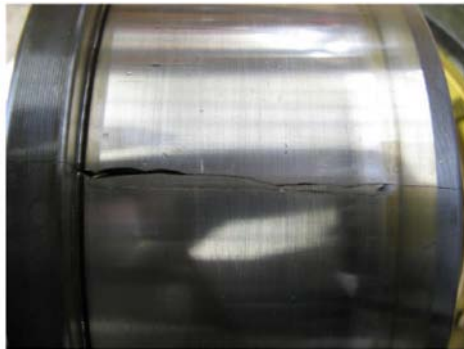
- This presentation is revealing research information and industrial solutions to increase the reliability of bearings applied in wind turbine gear units.



1. Introduction

- Several roller bearing applications are prone to the White Etching Crack (WEC) or irregular White Etching Area (irWEA) failure mode. The subsurface microstructure of a failed bearing contains changed material structures near cracks which are seen as white (and thus chemical inert) after a nital etching test.

Martensitic
bearing
steel



Bainitic
bearing
steel

1. Introduction

↯ The WEC/irWEA failure mode is observed on several roller bearing applications, with different bearing types from different suppliers.

↯ Some examples from the public domain :

- Automotive sector :

- pulley systems
- powertrains

- WTG

Wind Turbine Gearbox Reliability

The Nature of the Problem

by Don McVittie

(as channeled by Brian McNiff)

The elephant

Full-scale efforts are underway to solve the giant gearbox problems that are preventing these machines from reaching their full potential.



↯ The bearing applications seem to have in common a dynamic operation condition.

1. Introduction

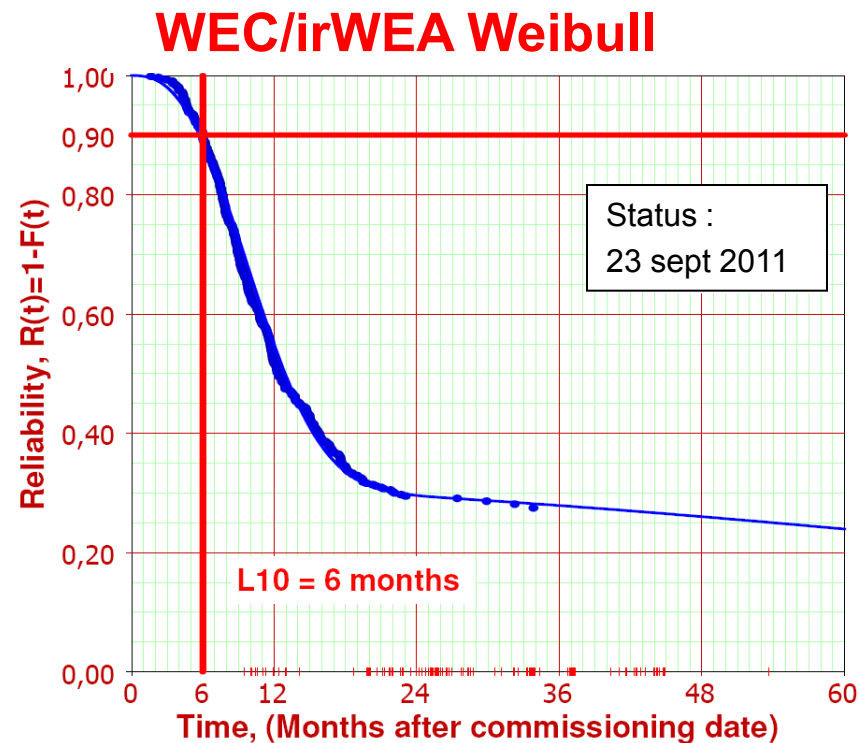
▮ Facts :

- calculated lifetime :
 - $L_{10h,ISO} = 24$ years
 - $L_{10h,FC} > 100$ years
- real lifetime $L_{10} = 6$ months

real lifetime is 50 times
lower then calculated
lifetime

▮ Conclusion :

WEC/irWEA \neq subsurface
material
fatigue



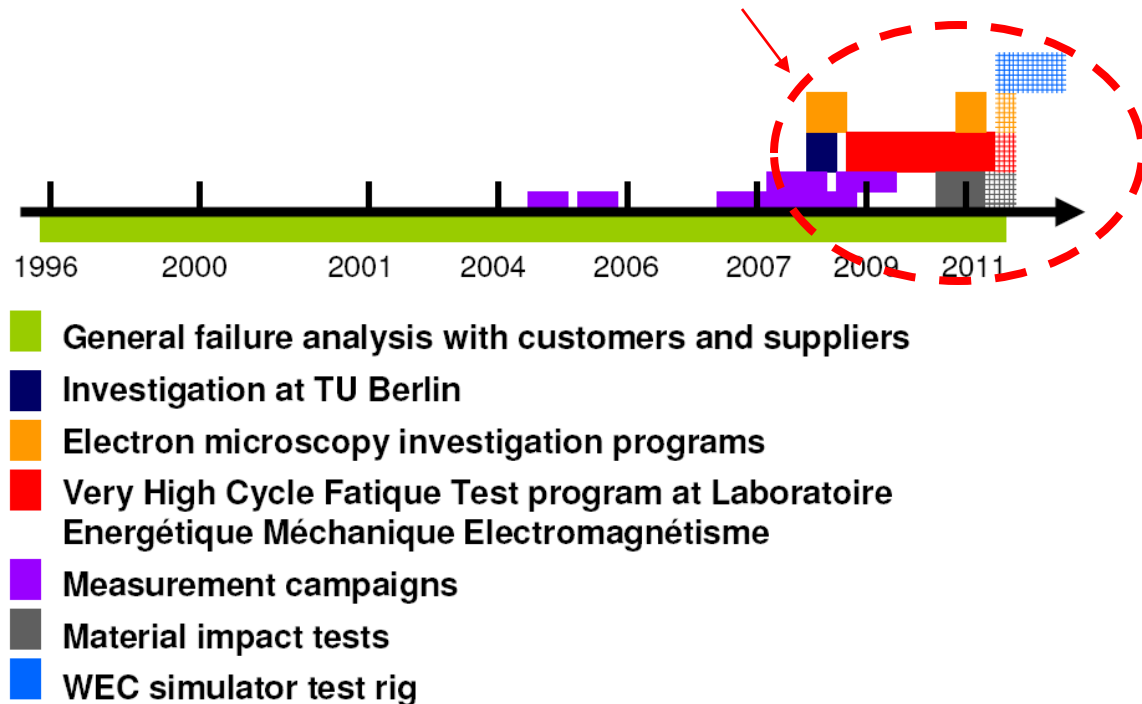
1. Introduction

- ▮ There is no industry wide agreed understanding of the WEC/irWEA failure mode. The different hypotheses are :
 - overload fatigue
 - hydrogen embrittlement
 - normal stress hypothesis
 - additional load mechanism :
 - mechanical impact
 - electrical
 - chemical
 - . . .

- ▮ In case of a WEC/irWEA bearing failure, best practice is applied.

1. Introduction

- ▮ The wind industry applications are suffering hard of the WEC/irWEA failure mode on roller bearings. By lack of solutions and understanding from the bearing suppliers, Hansen started independant WEC/irWEA research.



1. Introduction

- ▮ Focus area for WEC/irWEA research are the roller bearings in the **Hansen wind gear unit applications**
 - ▮ The evaluation of :
 - different hypotheses via :
 - load measurement campaigns
 - hydrogen measurements
 - material analysis
 - research results
 - . . .
 - Hansen wind experience :
 - identification of drivers
- ⇒ (hypothesis), formulation

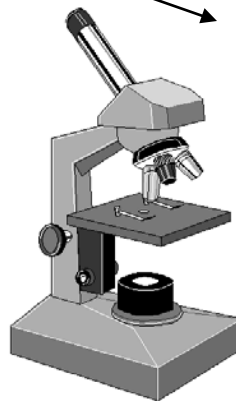
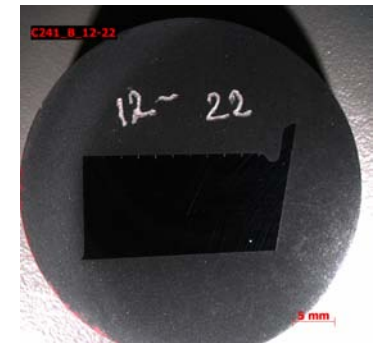
Agenda

- 1. Introduction
- 2. Material observations in WEC/irWEA failed bearings
- 3. Interpretation of material observations
- 4. Hansen wind experience
- 5. Hypothesis development & Material research
- 6. Proposals for WEC/irWEA research
- 7. Summary and way forward

2. Material observations

Microstructure etching tests :

- cut a sample out of a bearing
- embedding and polishing
- nital etching
- microscopic investigation

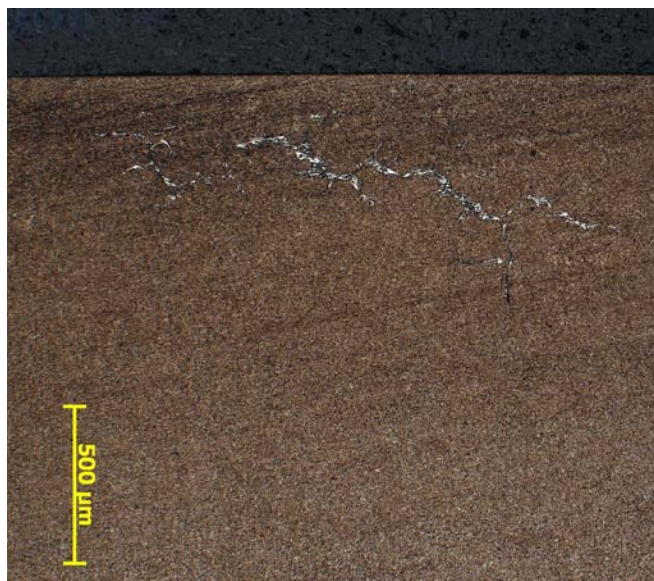


Case carburised bearing steel : WEC/irWEA failed bearings

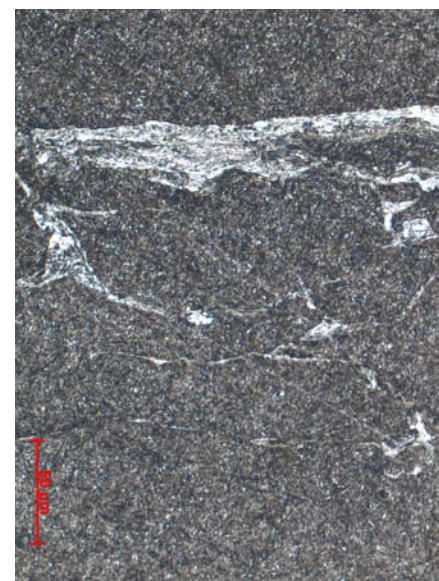
Subsurface networks with cracks and white etching area's



Small network



Large network



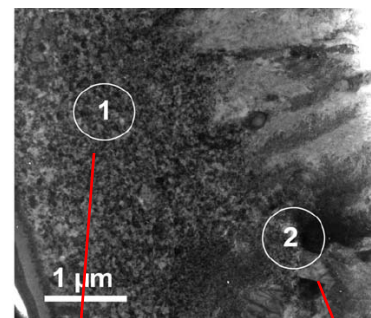
Close-up view

Bainitic bearing steel : WEC/irWEA failed bearings

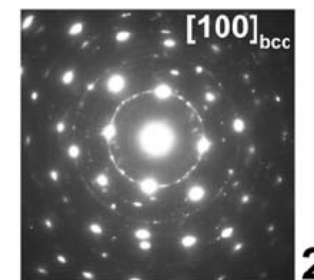
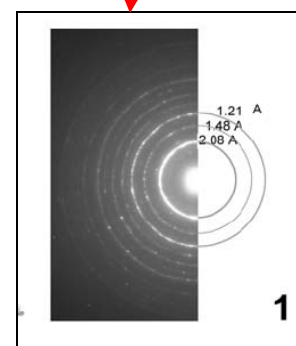
Subsurface
networks
with cracks
and white
etching
area's



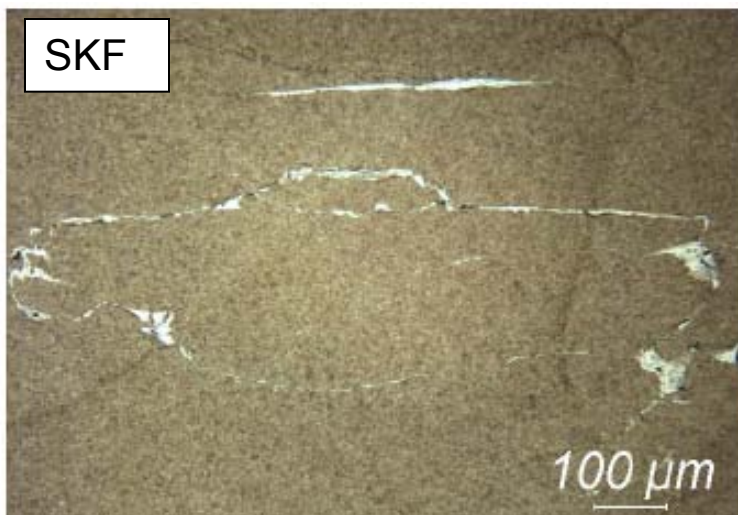
Electron
microscopy



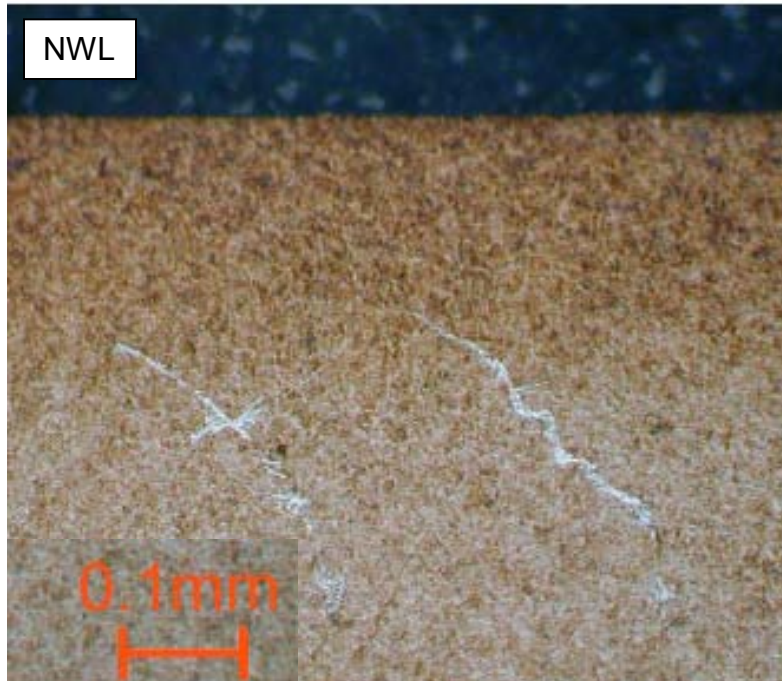
Electron
diffraction



Nanograins in white
etching material area's

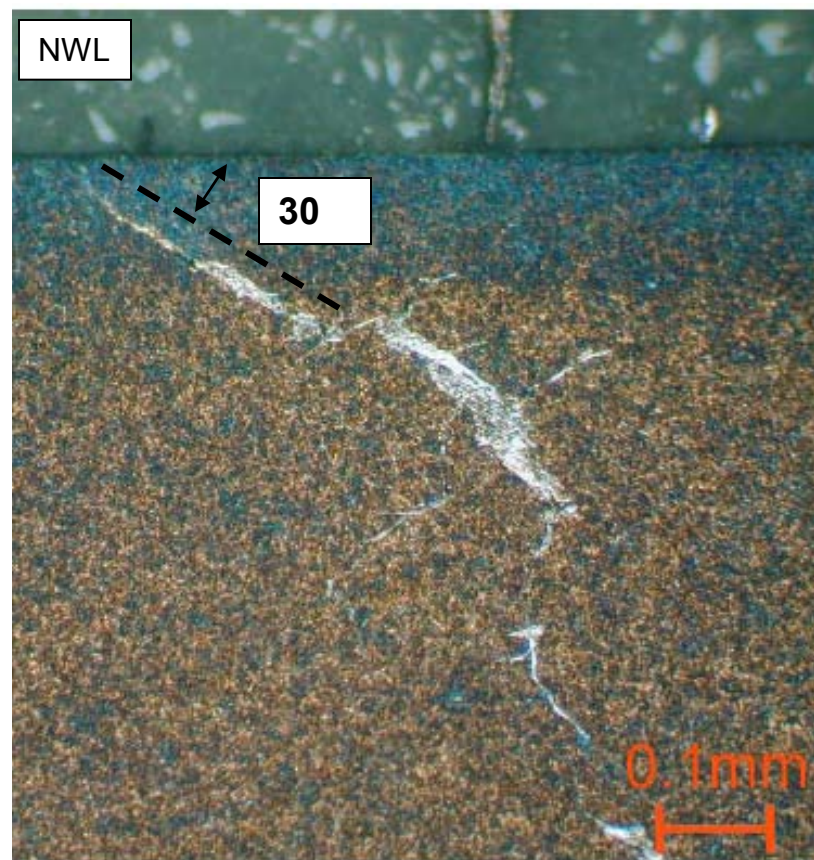
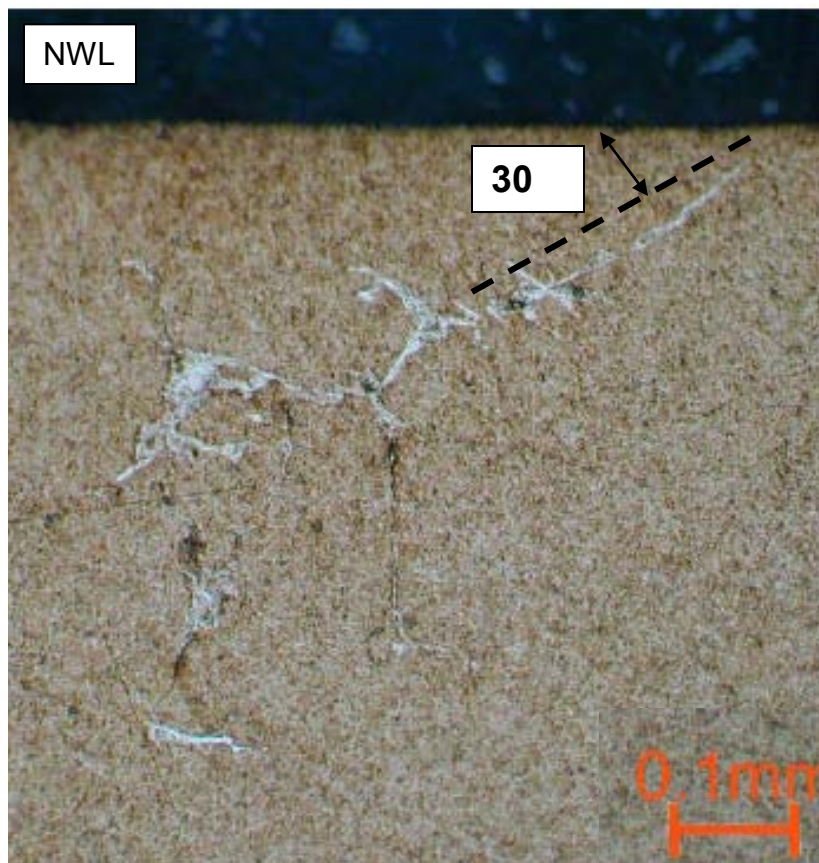


Martensitic bearing steel : WEC/irWEA failed bearings



Isolated small subsurface damage with white etching area's

Martensitic bearing steel : WEC/irWEA failed bearings

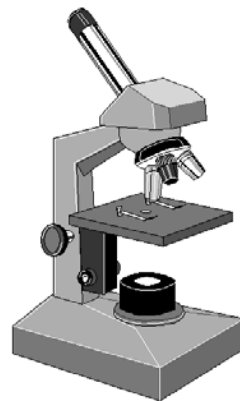
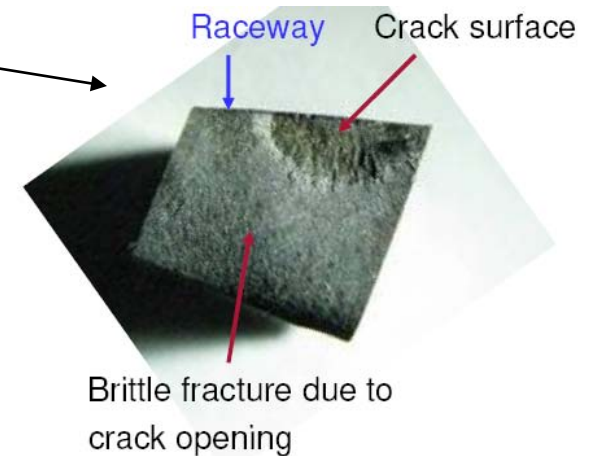


Subsurface damage with 30° oriented crack towards the raceway and white etching development

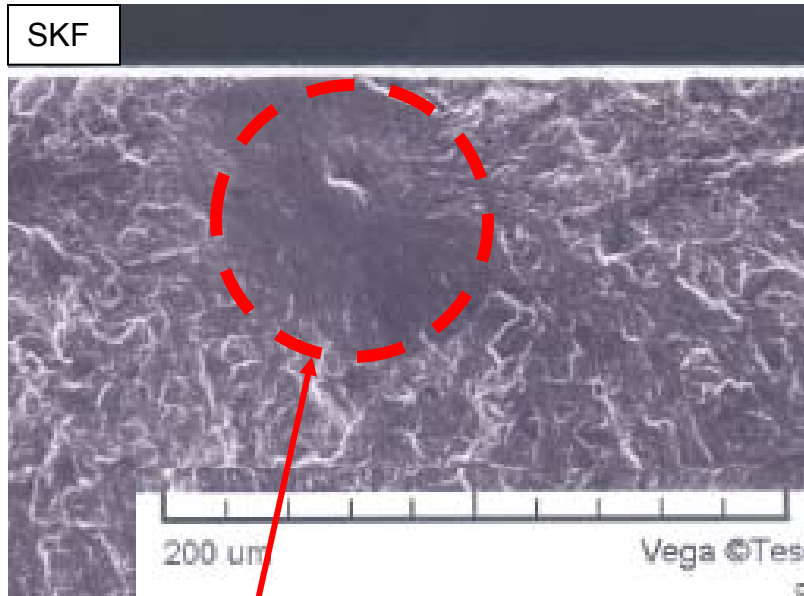
2. Material observations

Crack opening :

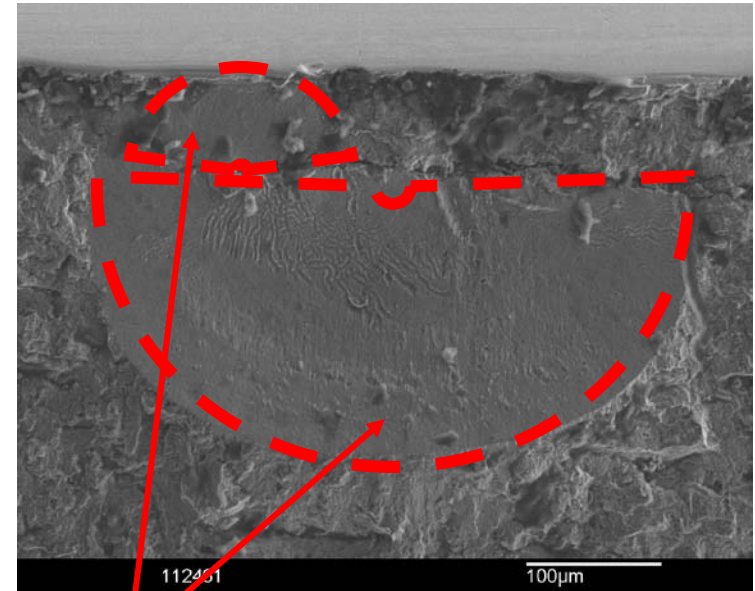
- select a small (recent) hairline crack
- cut the sample and open the crack
- investigate crack surface with (electronic) microscopy



Martensitic bearing steel : WEC/irWEA failed bearings

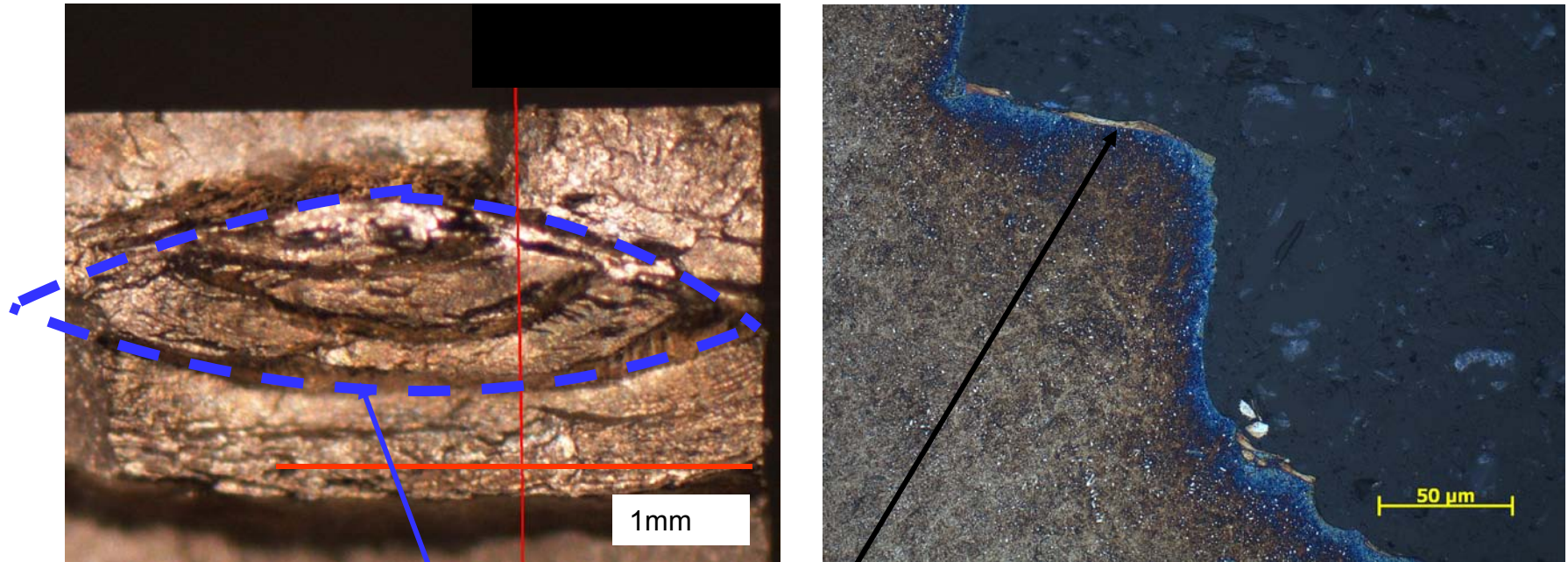


Circular crack around an inclusion/butterfly



Semi circular cracks around an inclusion

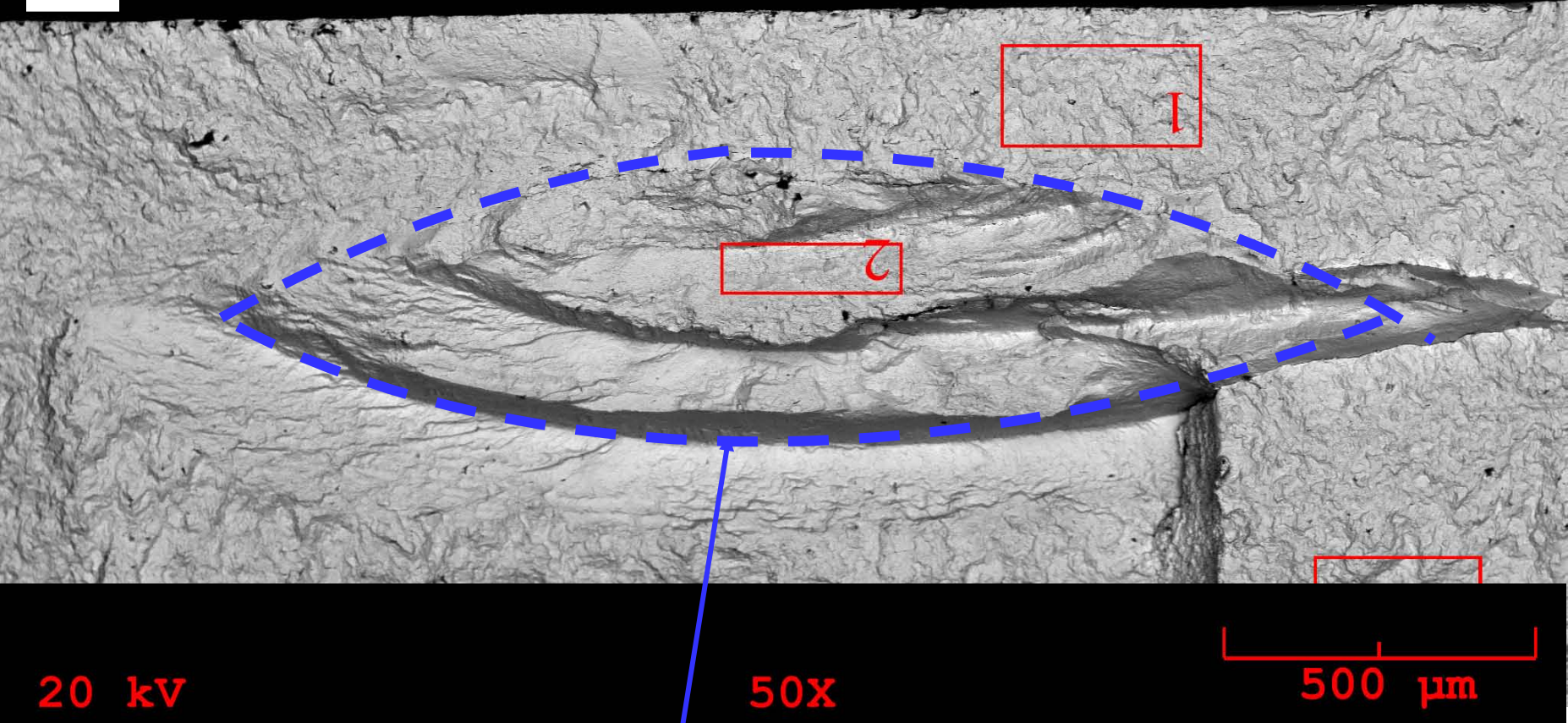
Martensitic bearing steel : WEC/irWEA failed bearings



V-segment with white etching material
area's in parallel part of the crack

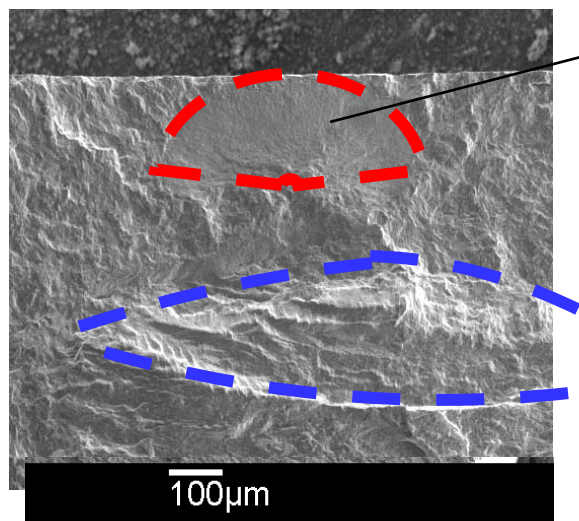
Martensitic bearing steel : WEC/irWEA failed bearings

NWL

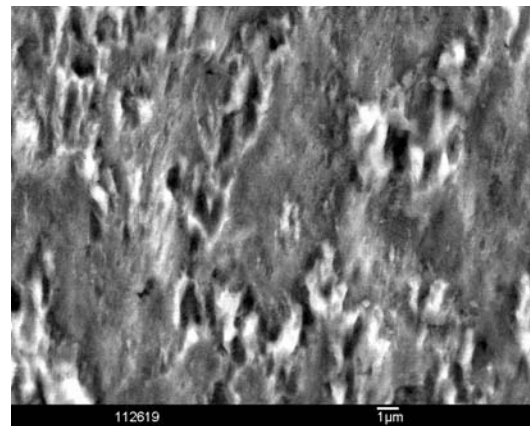


V-segment and

Martensitic bearing steel : WEC/irWEA failed bearings



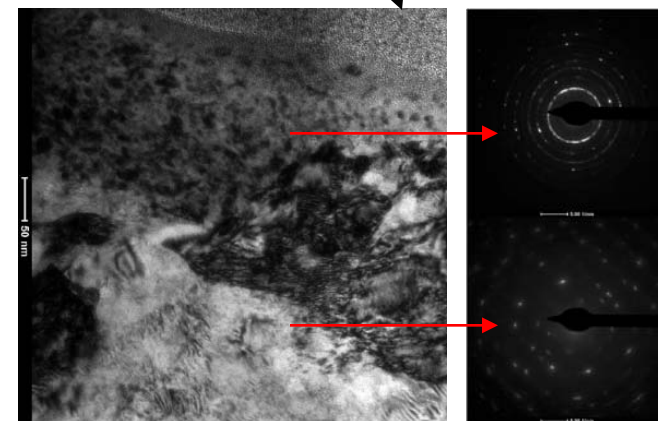
SEM
x 40



Flat crack surface with **voids**
surrounded by elevated borders

FIB
sample
and TEM
x 40

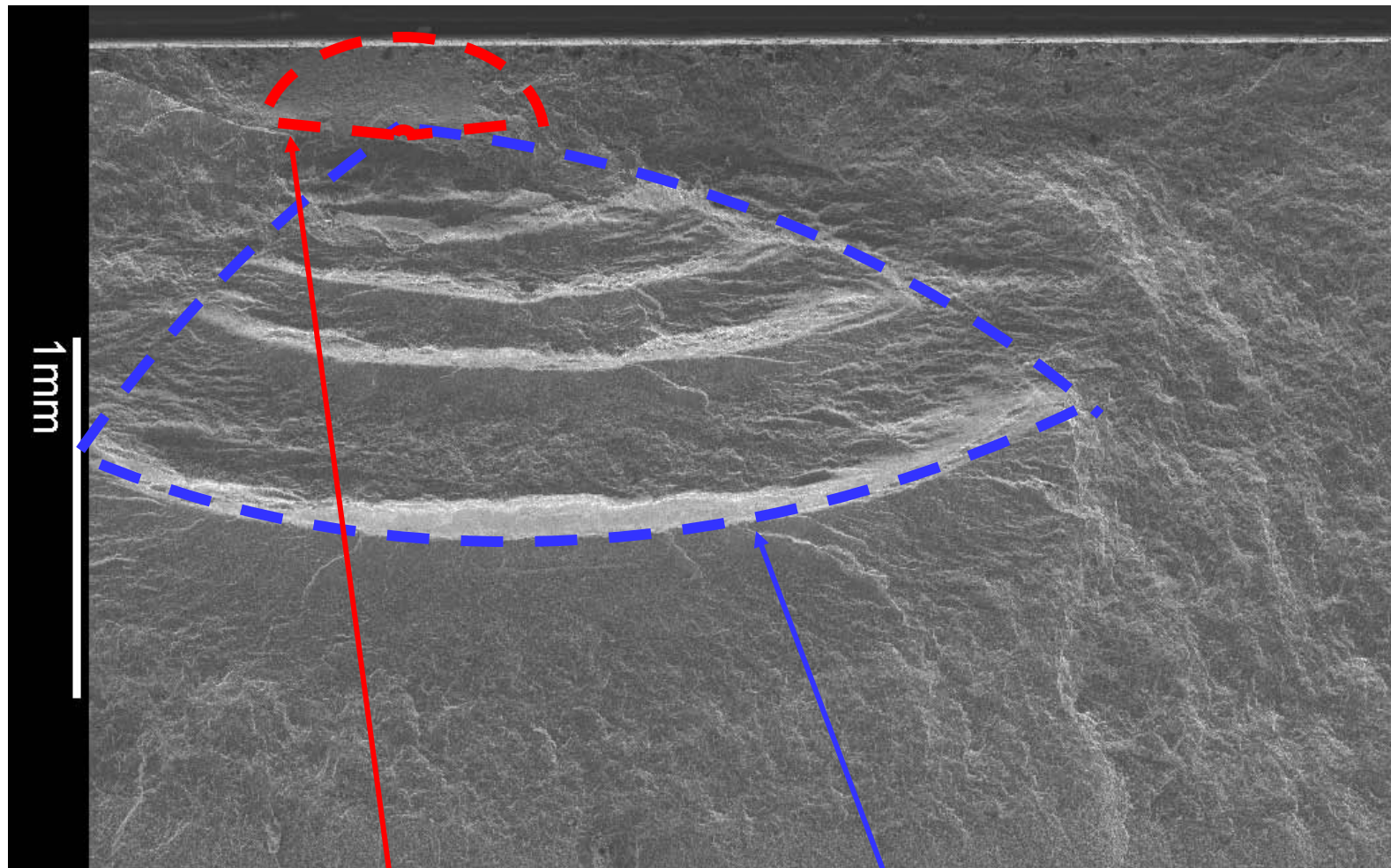
V-segment and semi
circular crack



Electron
diffraction

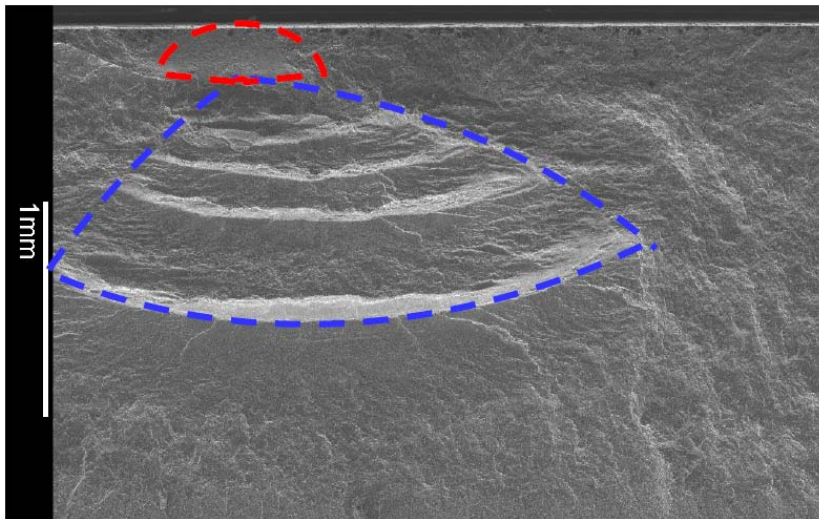
Nanograins at crack surface

Martensitic bearing steel : WEC/irWEA failed bearings



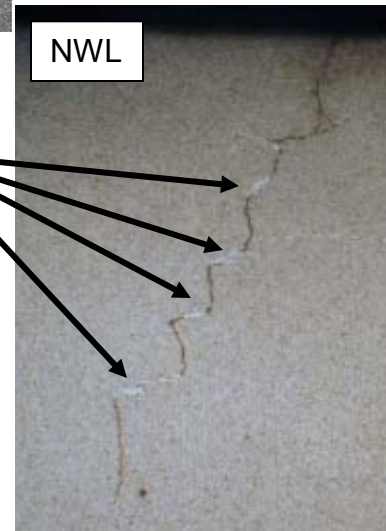
Semi circular crack and large V-segment

Martensitic bearing steel : WEC/irWEA failed bearings



Perpendicular
cutting (before
crack opening)
and later
microstructure
etching

Semi circular crack and large
V-segment with **white etching**
material area's in parallel parts
of the crack

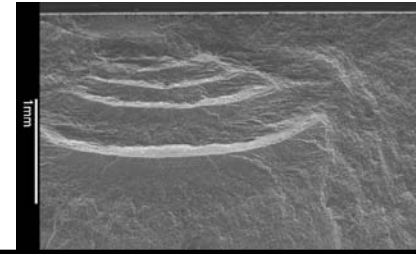
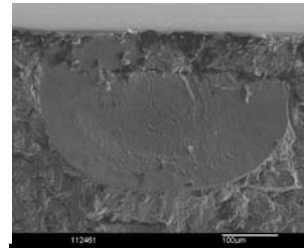


Agenda

- 1. Introduction
- 2. Material observations in WEC/irWEA failed bearings
- 3. Interpretation of material observations
- 4. Hansen wind experience
- 5. Hypothesis development & Material research
- 6. Proposals for WEC/irWEA research
- 7. Summary and way forward

Residual stress

- ▮ Martensitic : $\sim 100 / 150$ MPa tensile stress



Tensile stress \Rightarrow (semi) circular crack and V-segment

- ▮ Bainitic : $\sim 50 / 100$ MPa compressive stress
- ▮ Case carburised steel : $\sim 100 / 400$ MPa compressive stress

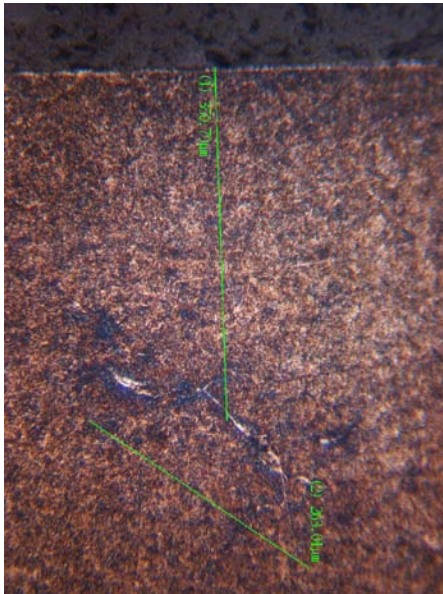


Compressive stress \Rightarrow large subsurface networks with cracks and white etching area's.



3. Interpretation of material observations

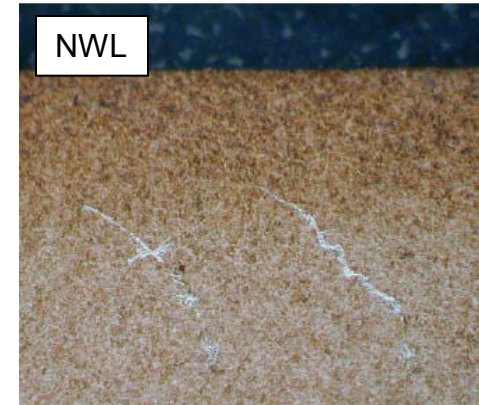
Small subsurface damage = local subsurface damage initiation



Bainite



Case carburised

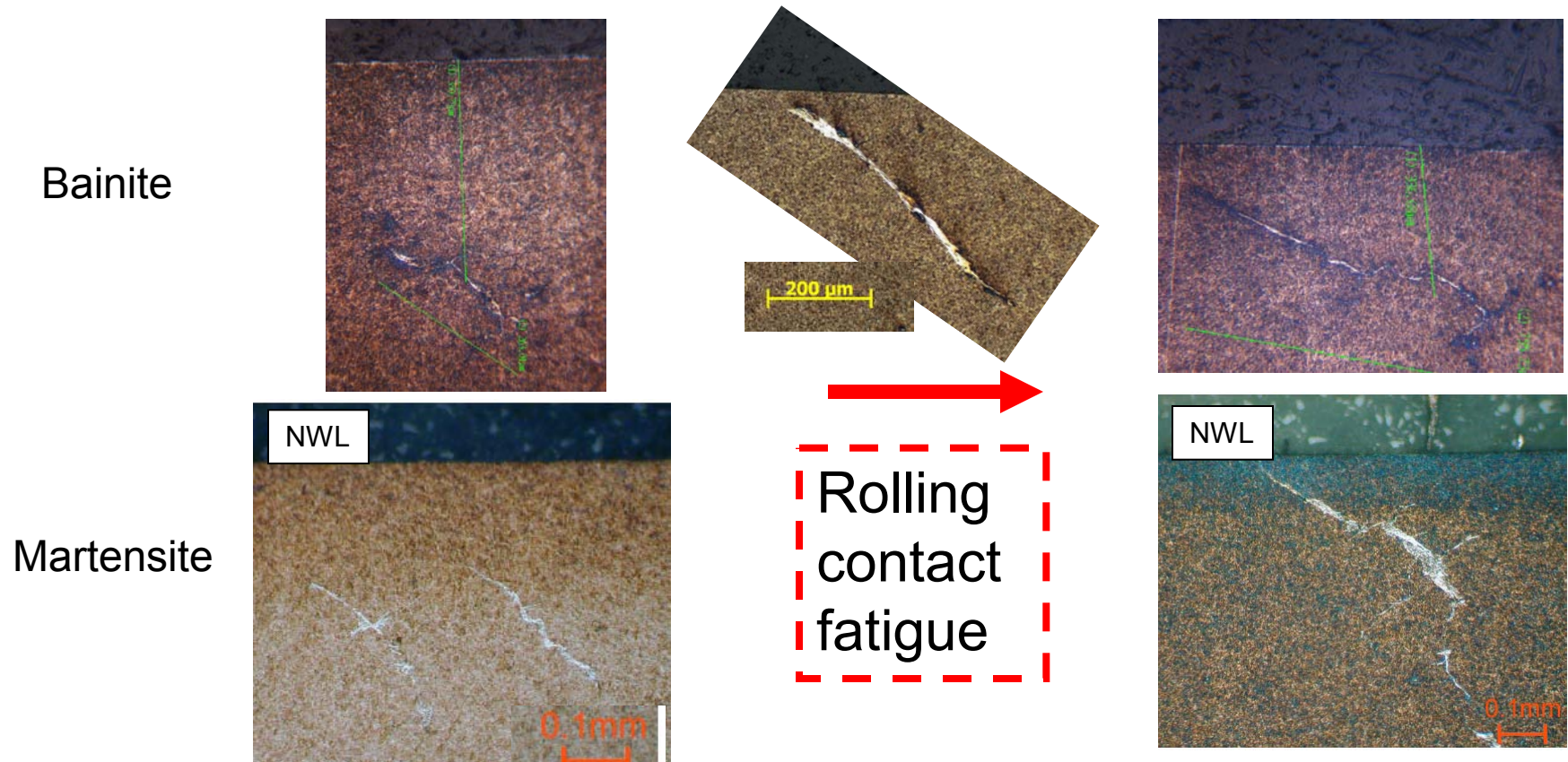


Martensite



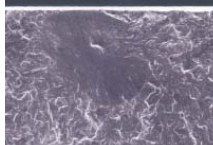
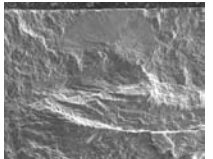
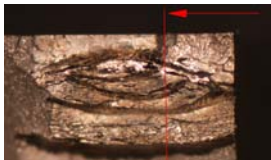
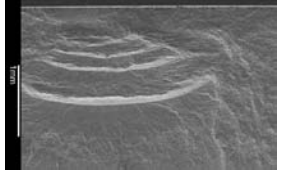


3. Interpretation of material observations



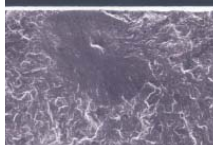
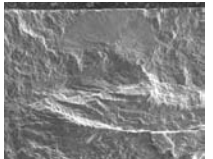
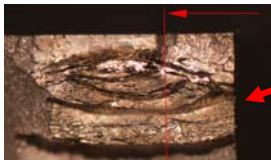

- Local subsurface damage initiation = big inclusion. Crack development via classical rolling contact fatigue towards the surface.





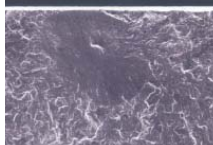
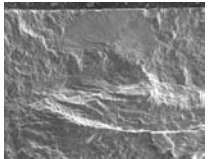
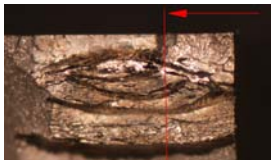
3. Interpretation of material observations

| Mat. observation | Severity classification | Interpretation of load system | Mat. interpretation |
|--|---|--|---------------------|
|  | Initiation phase, no bearing failure . Limited subsurface damage over about 0.1 – 0.2 mm length. | Severity classification of all material observations | |
|  | Progression of rolling contact fatigue, just before bearing failure (= raceway damage) | | |
|  | Failed bearing with axial hairline crack. Limited subsurface damage till about <u>0.2 mm depth</u> . | Below the red dashed line = failed ↓ | |
|  | Failed bearing with axial hairline crack. Moderate subsurface damage till about <u>0.7 mm depth</u> . | | |
|  | Failed bearing with axial hairline crack. Big subsurface damage till about <u>1.5 mm depth</u> . | | |
|  | | | |

3. Interpretation of material observations

| Mat. observation | Severity classification | Interpretation of load system | Mat. interpretation |
|--|--|--|---------------------|
|  | Initiation phase, no bearing failure . Limited subsurface damage over about 0.1 – 0.2 mm length. | | |
|  | Progression of rolling contact fatigue, just before bearing failure (= raceway damage) | | |
|  | Failed bearing with axial hairline crack. Limited subsurface damage till about 0.2 mm depth . | <div>Observed in the same bearing ⇨ is there a common additional load system ?</div> | |
|  | Failed bearing with axial hairline crack. Moderate subsurface damage till about 0.7 mm depth . | | |
|  | | | |
|  | Failed bearing with axial hairline crack. Big subsurface damage till about 1.5 mm depth . | | |

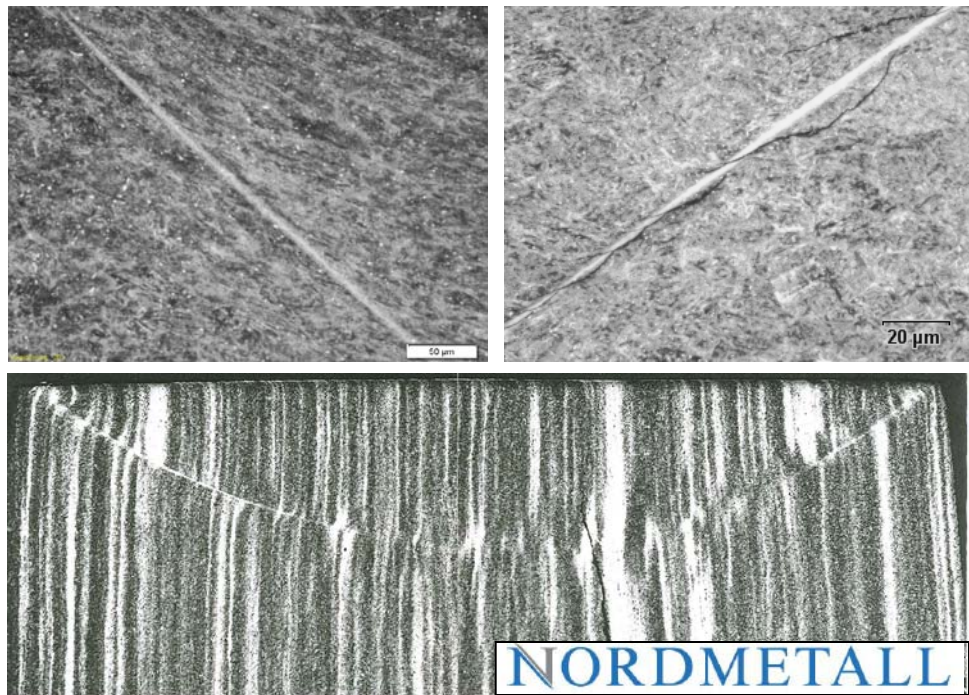
3. Interpretation of material observations

| Mat. observation | Severity classification | Interpretation of load system | Mat. interpretation |
|---|---|--|--|
|  | Initiation phase, no bearing failure . Limited subsurface damage over about 0.1 – 0.2 mm length. | Initiation by an <u>additional load system</u> | Link severity with load system(s) : - <u>additional load system</u> - RCE - inclusion |
|  | Progression of rolling contact fatigue, just before bearing failure (= raceway damage) | Initiation by an <u>additional load system</u> (= big inclusion) + rolling contact fatigue | |
|  | Failed bearing with axial hairline crack. Limited subsurface damage till about <u>0.2 mm depth</u> . | Local weak spot of inclusion and failure development by an <u>additional load system</u> at low level | |
|  | Failed bearing with axial hairline crack. Moderate subsurface damage till about <u>0.7 mm depth</u> . | (Initiation phase +) failure development by an <u>additional load system</u> at moderate level | |
|  | Failed bearing with axial hairline crack. Big subsurface damage till about <u>1.5 mm depth</u> . | (Initiation phase +) failure development by an <u>additional load system</u> at heavy level | |

3. Interpretation of material observations

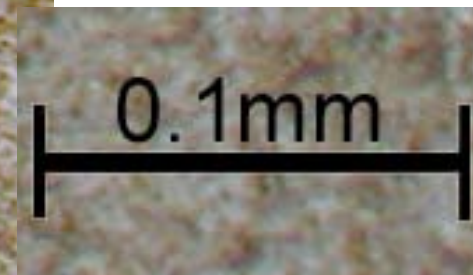
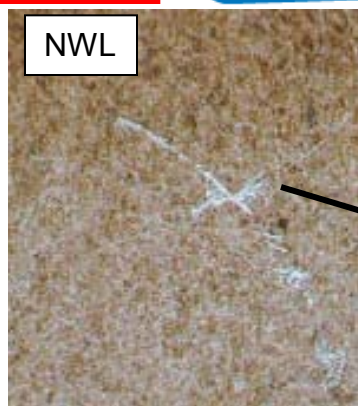
▮ Local subsurface damage initiation :

- adiabatic shear band (ASB) = straight or curved thin band
- nano grain sized microstructure, thus white etching
- generated by an impact load

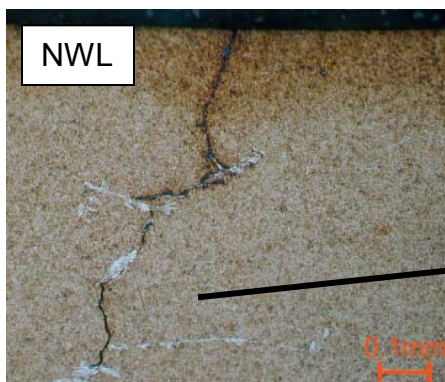
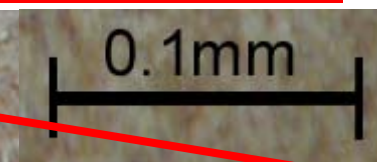
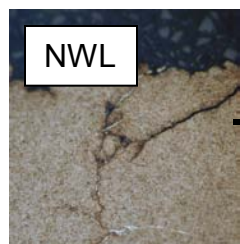


ASB in bearing steel (upper left and right) and 57HRC steel (lower) generated by an impact test

3. Interpretation of material observations



White bands are interpreted as adiabatic shear bands



Adiabatic shear band and crack

Crack propagation

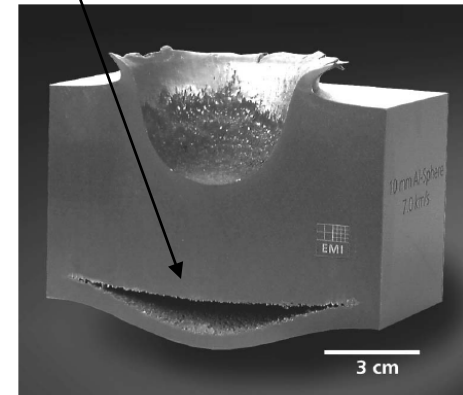
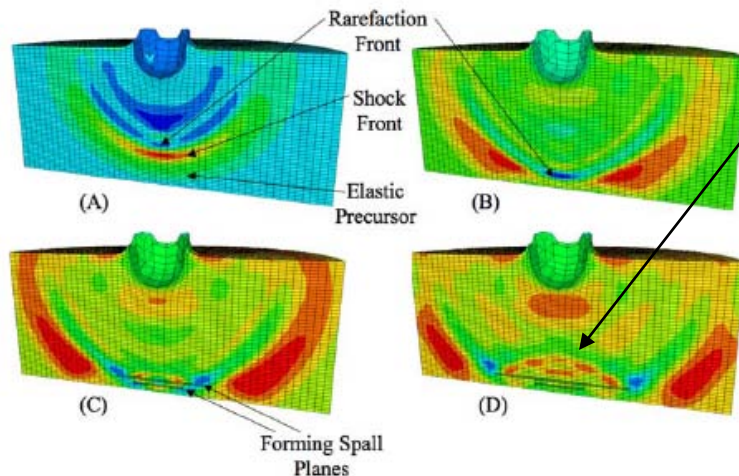
- + Development of white etching area's at the crack and ASB borders

Thus the ASB will be hidden after some time

3. Interpretation of material observations

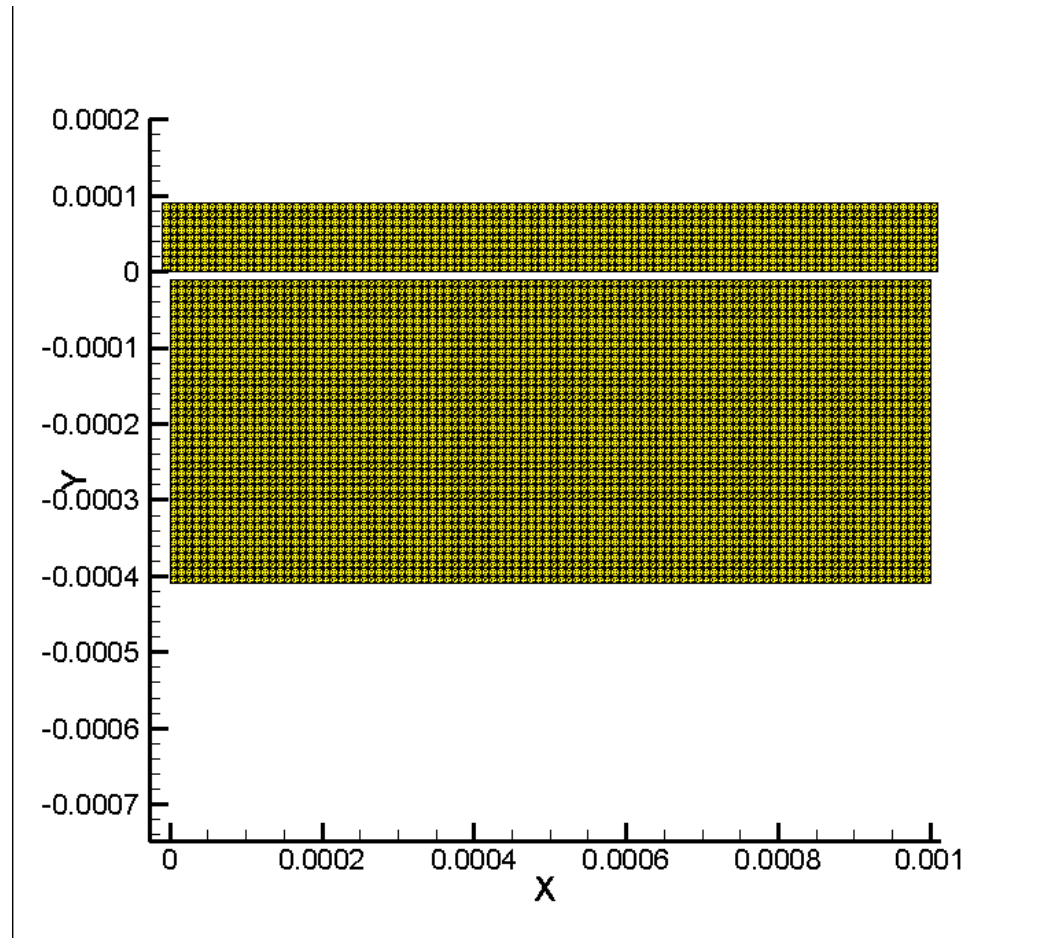
▮ Ballistic impact on a plate :

- impact \Rightarrow generation of longitudinal wave
- superposition of 2 tensile waves :
 - a) reflected wave at free surface = tensile wave
 - b) back side of longitudinal wave = tensile wave
- generation of an **elliptical cleavage crack = spallation**



Hiermaier S. J.,
Structures under
crash and impact

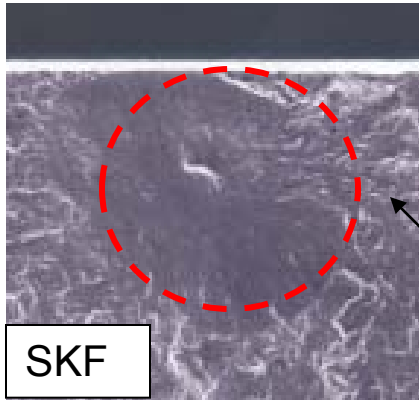
Spallation



Shaofan Li,
<http://www.ce.berkeley.edu/~shaofan/spall.html>

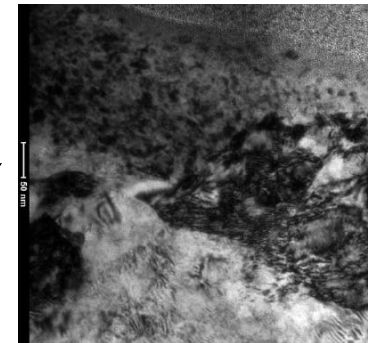
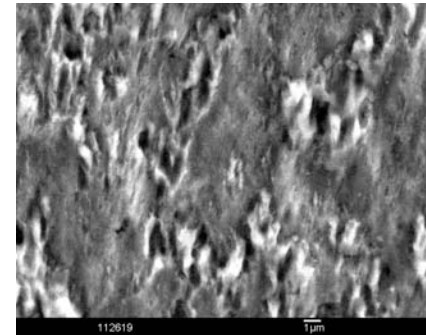
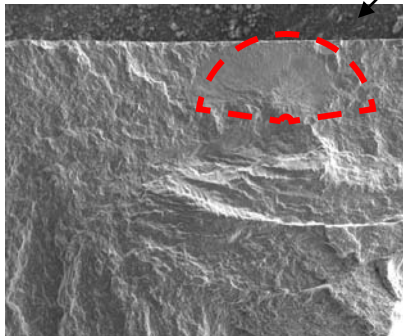
▮ (Semi) circular crack surface is interpreted as **spallation crack** from an impact load based on :

- circular shape with central origin
- surface morphology : flat and voids
- interaction with inclusions
- presence of nanograins on crack surface



SKF

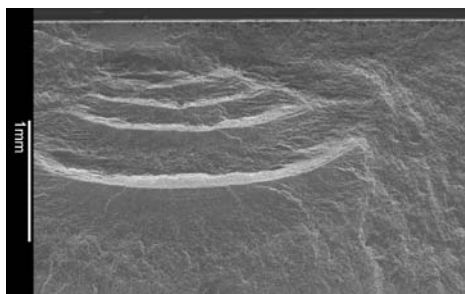
(Semi) circular
crack



3. Interpretation of material observations



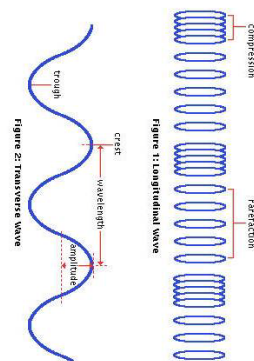
V-segment



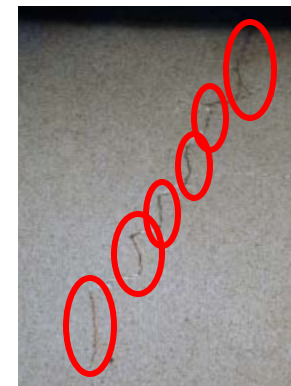
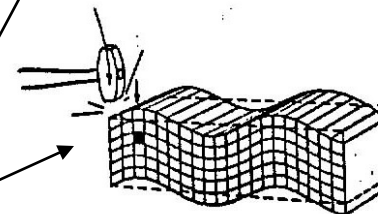
▮ V-segment is interpreted as crack surface from a wave load based on :

- V-spreading and stop with depth is propagation of a body wave
- stepped crack pattern : 2 wave systems generate cracks in 2 directions

Longitudinal wave
⇒ parallel cracks



Shear wave
⇒ radial cracks



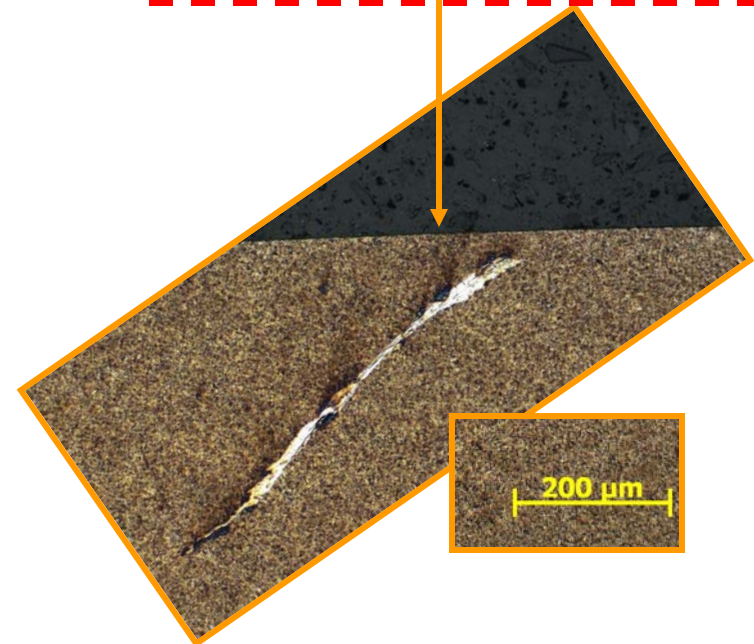
3. Interpretation of material observations



White etching at parallel part of the crack

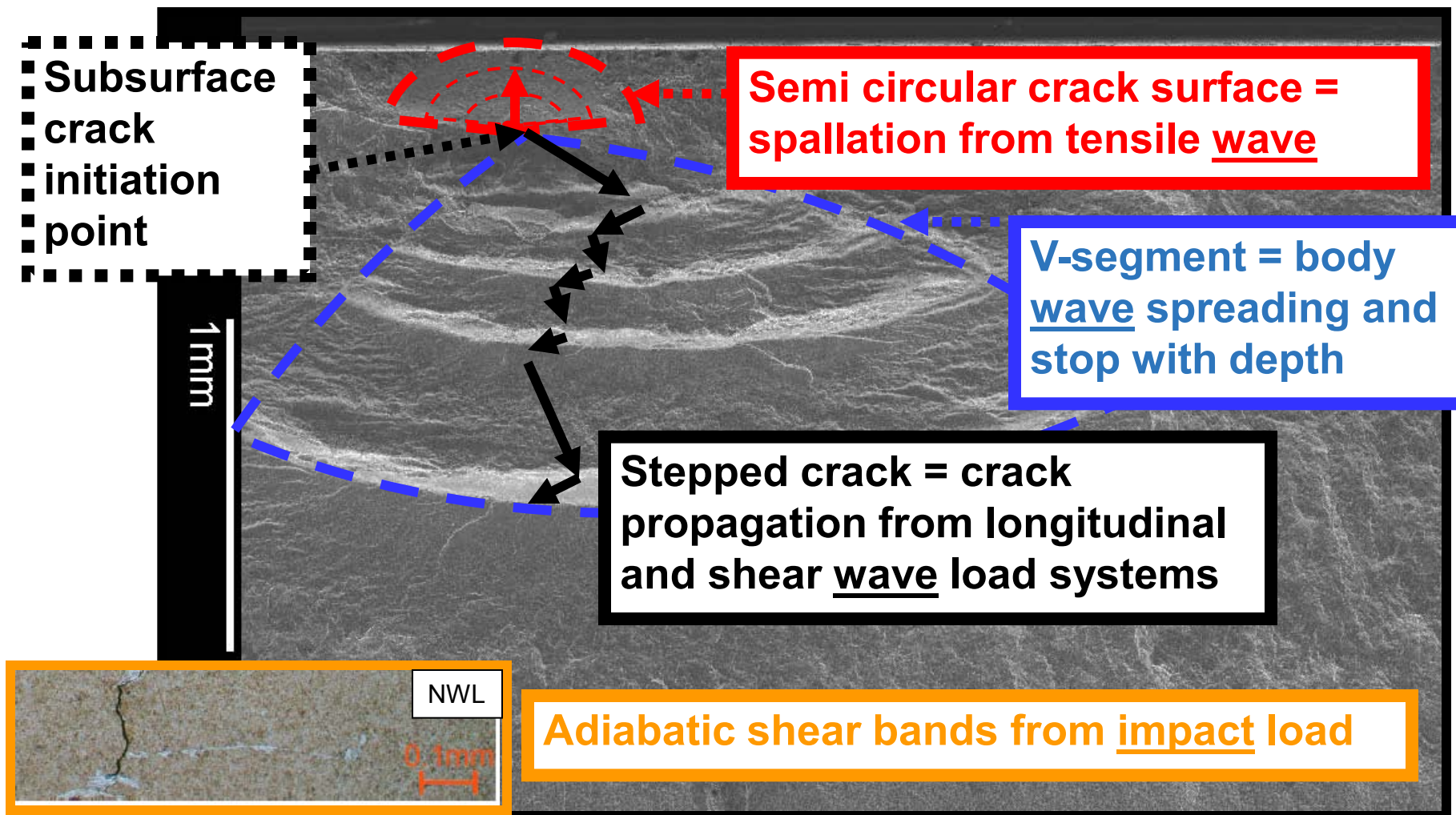


- White etching area's at parallel part of crack in V-segment :
 - identical generation mechanism as in rolling contact fatigue with crack development
 - and thus consequential damage




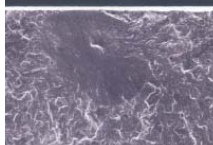
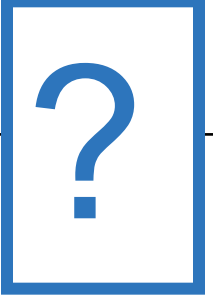
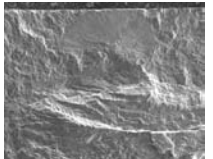
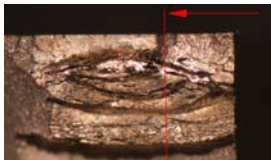



3. Interpretation of material observations


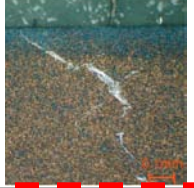
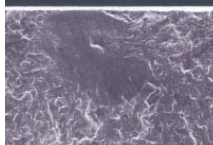
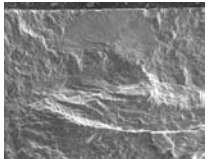
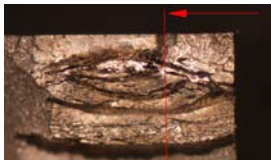
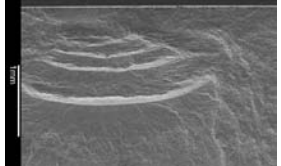
▮ Martensitic WEC/irWEA failed bearing



3. Interpretation of material observations

| Mat. observation | Severity classification | Interpretation of load system | Mat. interpretation |
|---|--|--|--|
|  | Initiation phase, no bearing failure . Limited subsurface damage over about 0.1 – 0.2 mm length. | Initiation by an <u>additional load system</u> |  |
|  | Progression of rolling contact fatigue, just before bearing failure (= raceway damage) | Initiation by an <u>additional load system</u> (= big inclusion) + rolling contact fatigue | |
|  | Failed bearing with axial hairline crack. Limited subsurface damage till about <u>0.2 mm depth.</u> | Local weak spot of inclusion and failure development by an <u>additional load system</u> at low level |  |
|  | Failed bearing with axial hairline crack. Moderate subsurface damage till about <u>0.7 mm depth.</u> | (Initiation phase +) failure development by an <u>additional load system</u> at moderate level | |
|  | Failed bearing with axial hairline crack. Big subsurface damage till about <u>1.5 mm depth.</u> | (Initiation phase +) failure development by an <u>additional load system</u> at heavy level |  |

3. Interpretation of material observations

| Mat. observation | Severity classification | Interpretation of load system | Mat. interpretation |
|--|---|--|---|
|  | Initiation phase, no bearing failure . Limited subsurface damage over about 0.1 – 0.2 mm length. | Initiation by an <u>additional load system</u> | Initiation = Adiabatic shear band and crack from an <u>impact load</u> . |
|  | Progression of rolling contact fatigue, just before bearing failure (= raceway damage) | Initiation by an <u>additional load system</u> (= big inclusion) + rolling contact fatigue | <u>White etching = consequential damage that hides the ASB</u> |
|  | Failed bearing with axial hairline crack. Limited subsurface damage till about <u>0.2 mm depth</u> . | Local weak spot of inclusion and failure development by an <u>additional load system</u> at low level | Spallation crack surface from an <u>impact load</u> |
|  | Failed bearing with axial hairline crack. Moderate subsurface damage till about <u>0.7 mm depth</u> . | (Initiation phase +) failure development by an <u>additional load system</u> at moderate level | Spallation crack surface, V-segment and stepped crack pattern from an <u>impact load</u> |
|  | | | |
|  | Failed bearing with axial hairline crack. Big subsurface damage till about <u>1.5 mm depth</u> . | (Initiation phase +) failure development by an <u>additional load system</u> at heavy level | <u>White etching = consequential damage</u> |

Conclusions :

The WEC/irWEA bearing material failure mode

=

Subsurface impact damage

(and the white etching area's are consequential damage)

The additional load system

=

IMPACT

Agenda

- 1. Introduction
- 2. Material observations in WEC/irWEA failed bearings
- 3. Interpretation of material observations
- 4. Hansen wind experience
- 5. Hypothesis development & Material research
- 6. Proposals for WEC/irWEA research
- 7. Summary and way forward

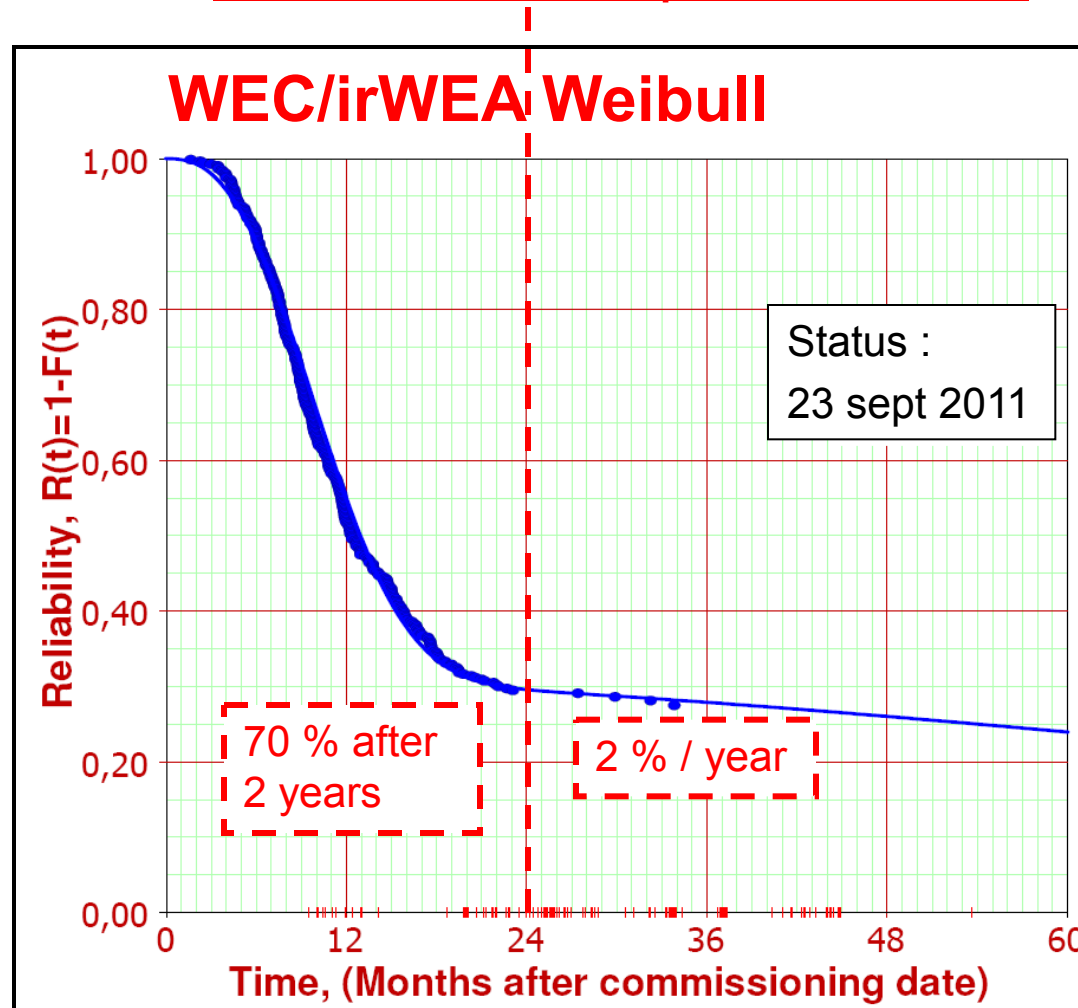
4. Hansen wind experience

- Promoting the WEC/irWEA bearing failure mode :
 - SRB and BB
 - big roller size
 - high dynamic bearing applications

- Preventing the WEC/irWEA bearing failure mode :
 - "operation time"
 - "case carburised"
 - black oxidised
 - hot assembly

4. Hansen wind experience

- ▢ The WEC/irWEA Weibull shows a significant drop of the failure rate after a certain operation time.



4. Hansen wind experience

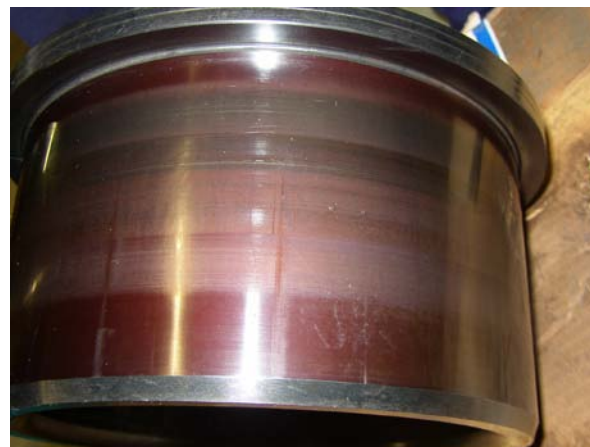
Black oxidised
performance :

**Significant
performance
increase**

| Version | Gearbox population | WEC/irWEA failure rate | After |
|---|-----------------------|---------------------------|---------|
| Standard CRB (bainite & martensite) | 1000 | 40 % ↔ 70 % | 2 years |
| Black oxidised CRB (bainite) | 1150 | 0,1 % | 2 years |

Black oxidised :

- controlled oxidation of the raceway
- iron oxide layer : 1 ↔ 2 μm thick
- improved run in behaviour



4. Hansen wind experience

Case carburised WEC/irWEA performance :

| Microstructure | Assembly temperature | Gearbox population | WEC/irWEA failure rate | After |
|-----------------------------|----------------------|--------------------|------------------------|-----------|
| Through hardened martensite | 100 C | 400 | 40 % | 14 months |
| Case carburised | 100 C | 57 | 5,3 % | 11 months |
| | 110 ↔ 120 C | 109 | 1.8 % | 16 months |

Conclusions :

- case carburised of a certain bearing supplier is **an improvement, but not a full robust solution**
- preventing influence of increased **assembly temperature**

4. Hansen wind experience

Increased bearing assembly temperature

| Bearing assembly temperature | Gearbox population | WEC/irWEA failure rate | After |
|------------------------------|--------------------|------------------------|-----------|
| 100 C | 400 | 40 % | 14 months |
| 110 C | | 12 % | |
| 130 C | 34 | 0 % | 35 months |
| 110 ↔ 120 C | 41 | 7.3 % | 15 months |

Bearing assembly temperature :

- WEC/irWEA failure mode is put on / off / on by different bearing assembly temperatures
- accurate data

Agenda

- 1. Introduction
- 2. Material observations in WEC/irWEA failed bearings
- 3. Interpretation of material observations
- 4. Hansen wind experience
- 5. Hypothesis development & Material research
- 6. Proposals for WEC/irWEA research
- 7. Summary and way forward

Interpretation of material observations

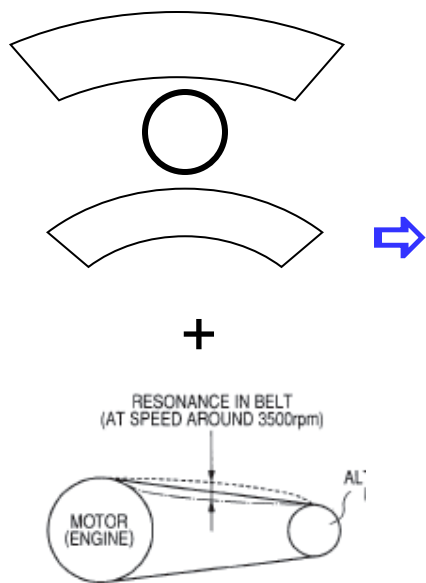


subsurface
impact
damage



WEC/irWEA
bearing
failure

IMPACT LOAD

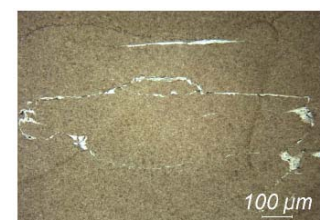
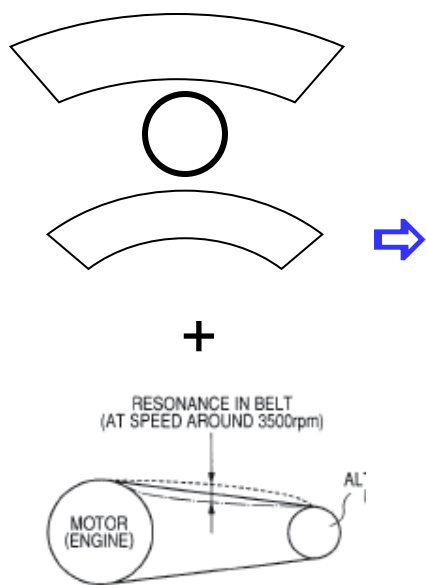


**Test
observations**



roller bearing
+
**dynamic load
conditions**
from application

WEC/irWEA
bearing
failure



roller bearing
+
dynamic load
conditions
from application

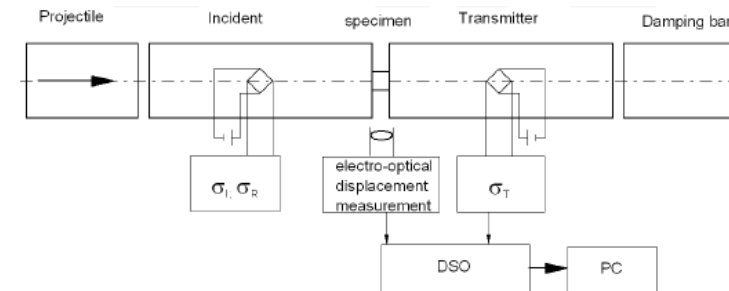
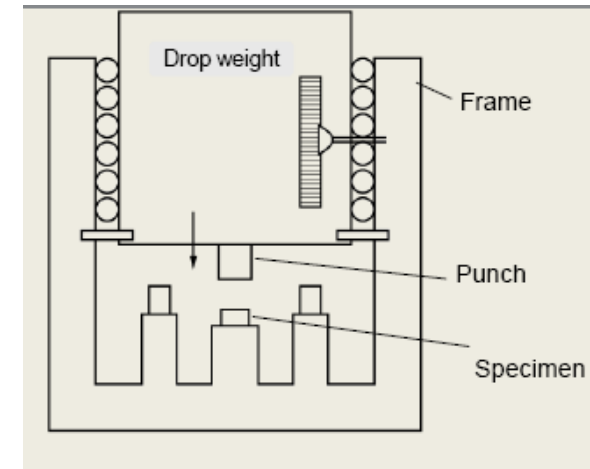
what is the
missing link
in the chain
of events ?
IMPACT LOAD

subsurface
impact
damage

WEC/irWEA
bearing
failure

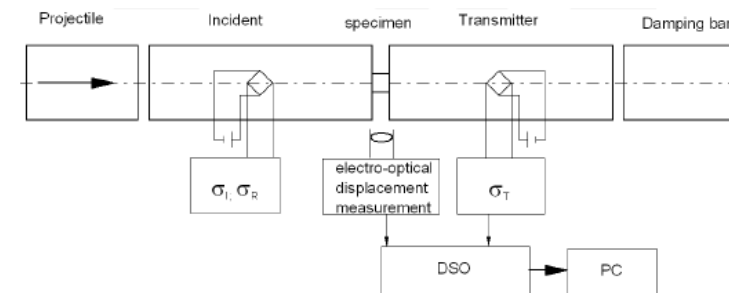
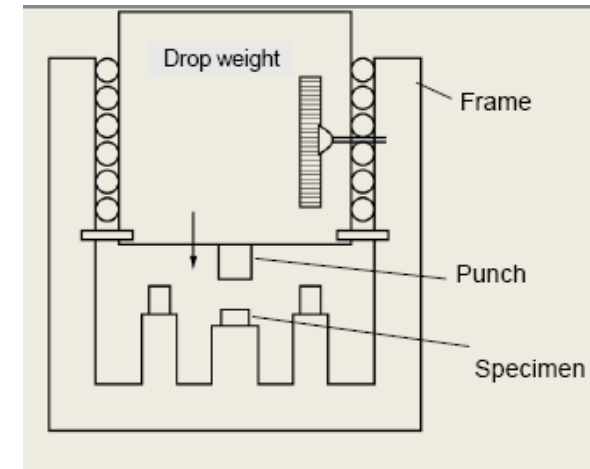
Impact tests :

- working hypothesis : CC, BO and HA bearing versions have a higher **impact** loadability then a standard M or B bearing
- action plan : do **impact** tests and compare all the variants
- test results :



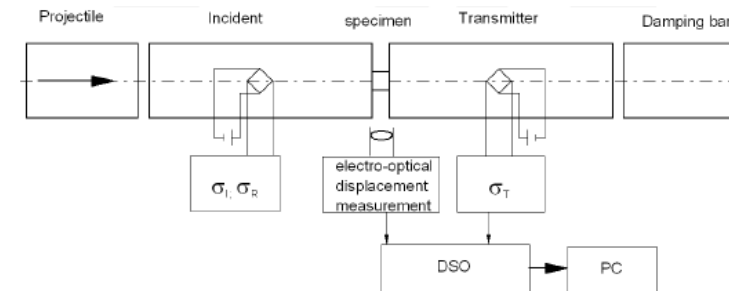
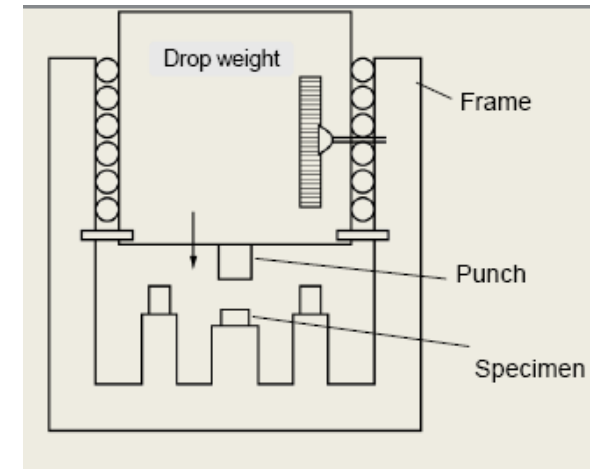
Impact tests :

- ~~working hypothesis : CC, BO and HA bearing versions have a higher impact loadability then a standard M or B bearing~~
- action plan : do impact tests and compare
- test results : low impact loadability but **no differentiation !!!**
- interpretation : CC, BO and HA are better then standard M or B :



Impact tests :

- ~~working hypothesis : CC, BO and HA bearing versions have a higher impact loadability then a standard M or B bearing~~
- action plan : do impact tests and compare
- test results : low impact loadability but **no differentiation !!!**
- interpretation : CC, BO and HA are better then standard M or B :
 - ~~higher impact loadability~~
 - no generation** of impact loads

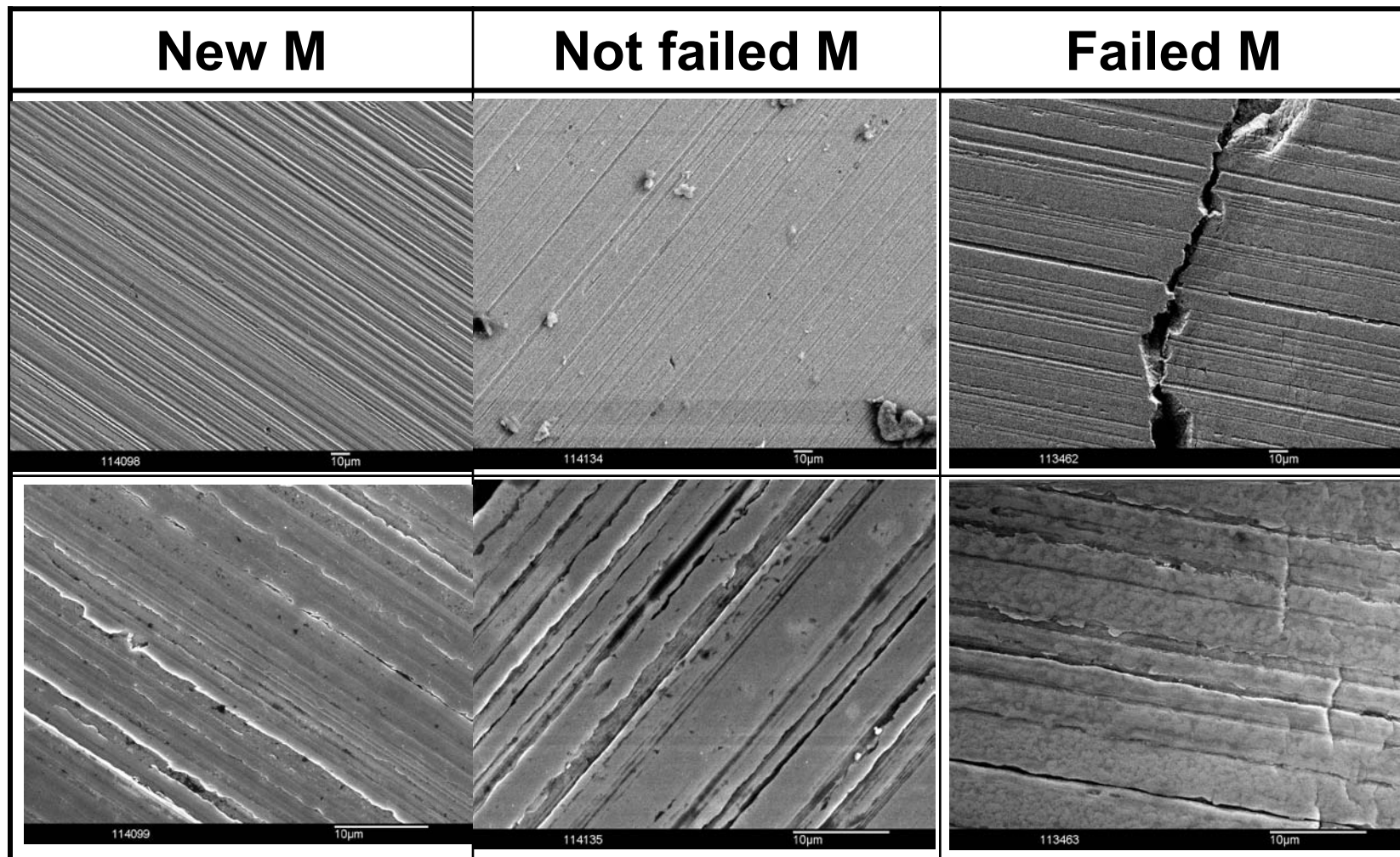


- ▮ Preventing drivers :
 - "operation time"
 - "case carburised"
 - black oxidised
 - hot assembly

- ▮ Is there a **common factor** that can be linked with generation of impact loads ?

- ▮ Where to look ? Previous research ⇨ reduced FWHM at **raceway surface**

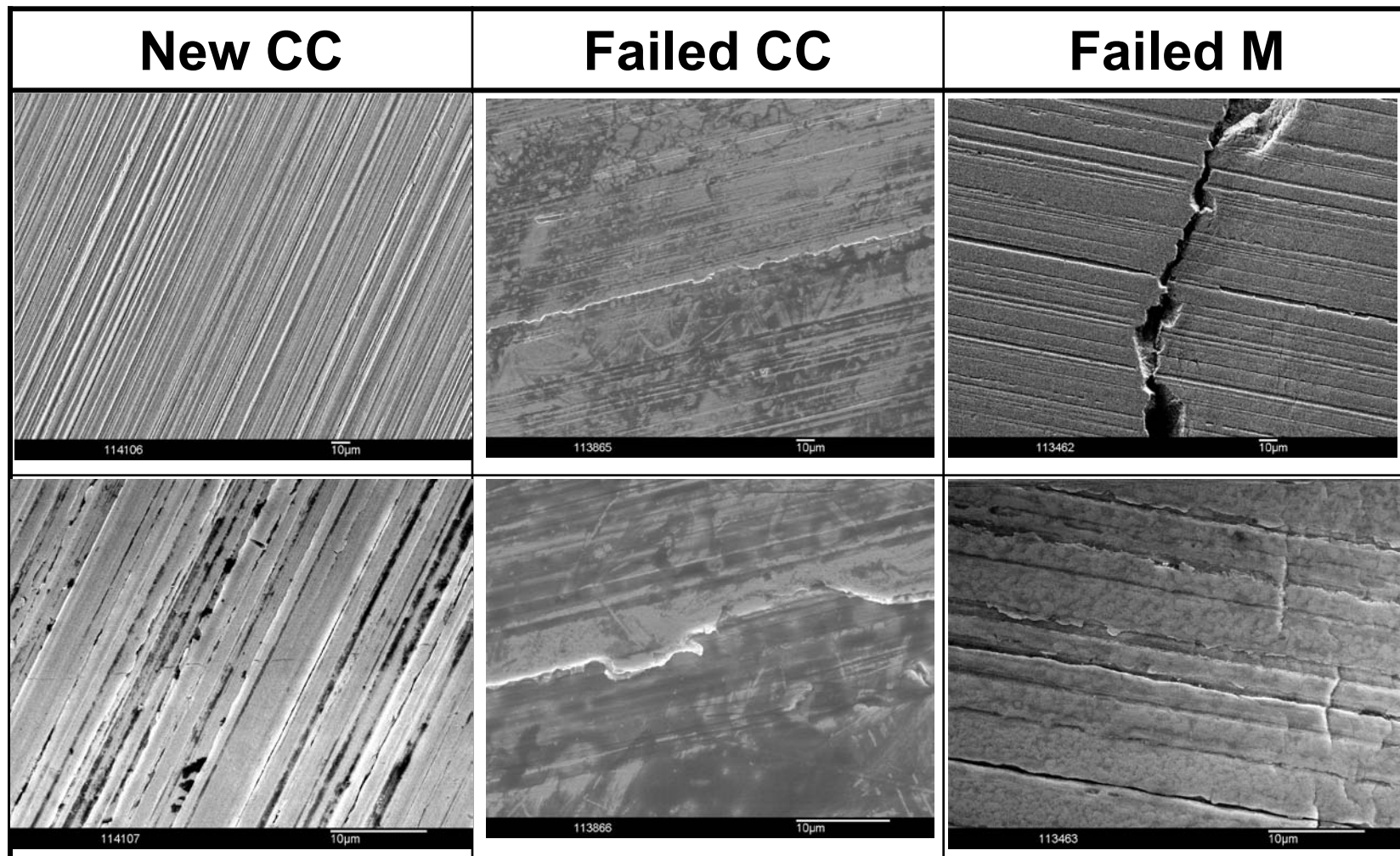
Comparison of raceway surface : **martensitic** = M



Hammered appearance of raceway surface in a WEC/irWEA critical application.

5. Hypothesis development & Material research

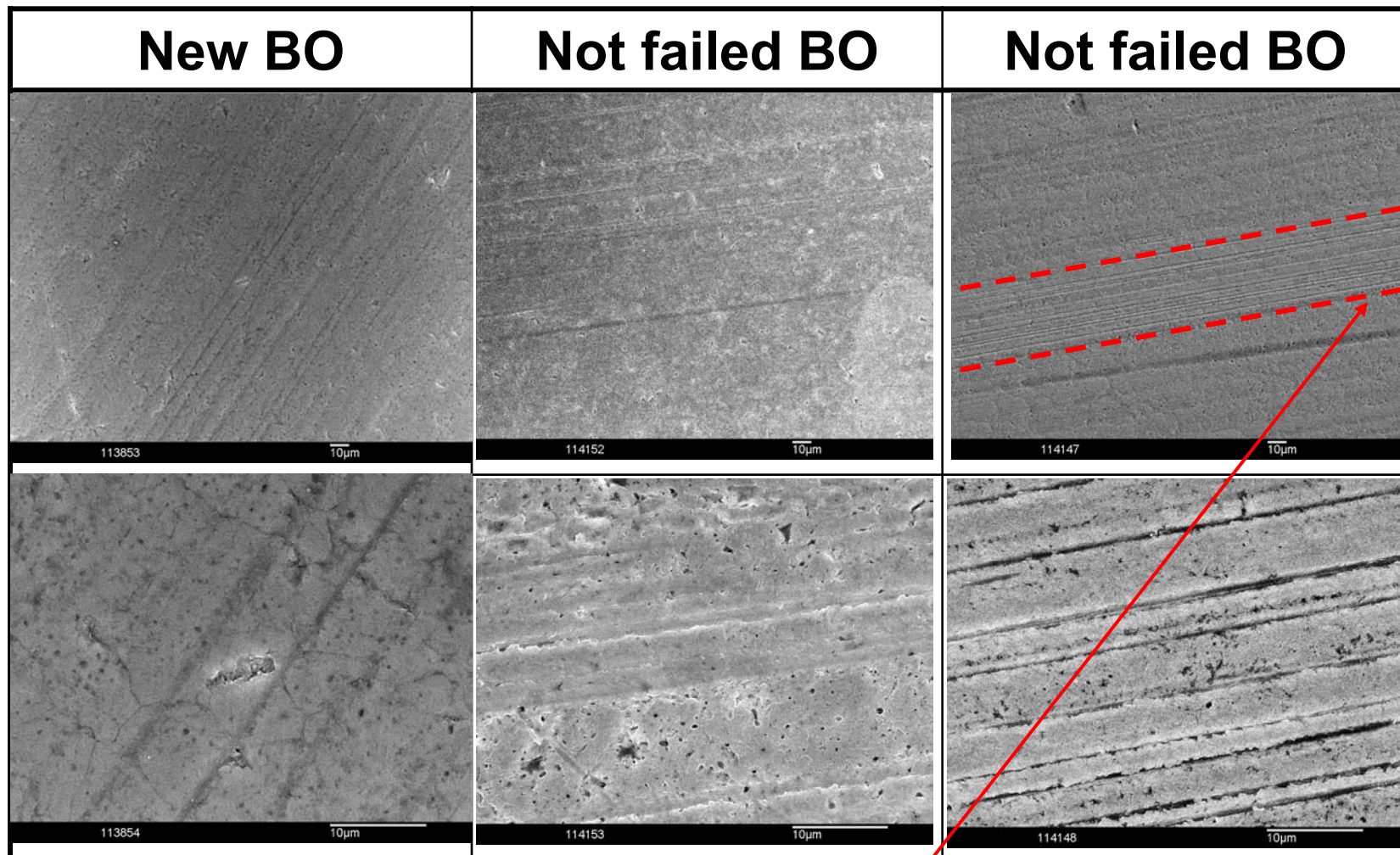
Comparison of raceway surface : case carburised = CC



Hammering appearance on raceway surface is **smaller** in comparison with martensite. Some case carburised asperities tops have minor flattening.

5. Hypothesis development & Material research

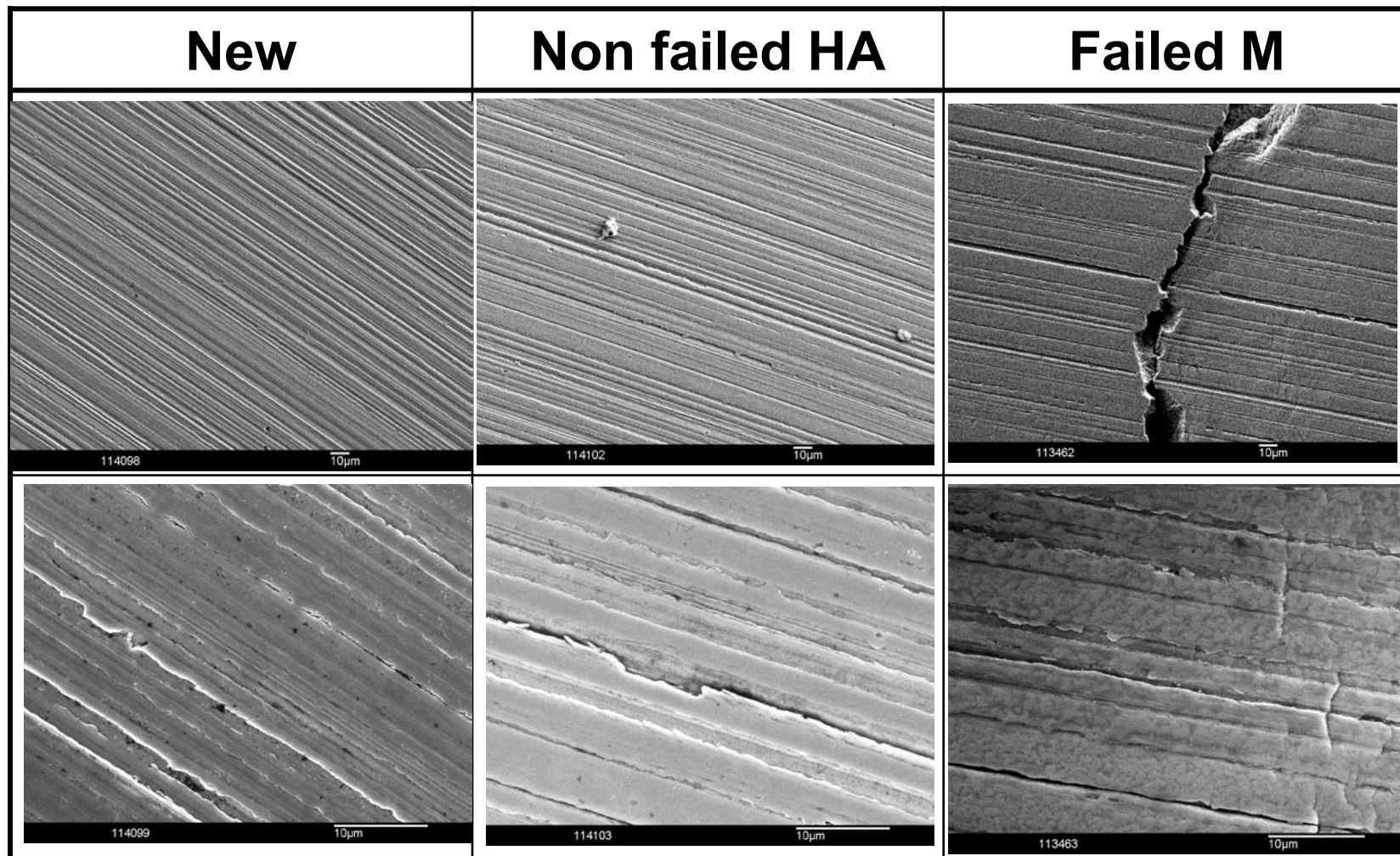
Comparison of raceway surface : black oxidised = BO



Black oxidised coating limits the development of hammered appearance to isolated lines or small bands

5. Hypothesis development & Material research

Comparison of raceway surface : assembly at 130 C = HA



Visual appearance is less hammering for HA compared to M.

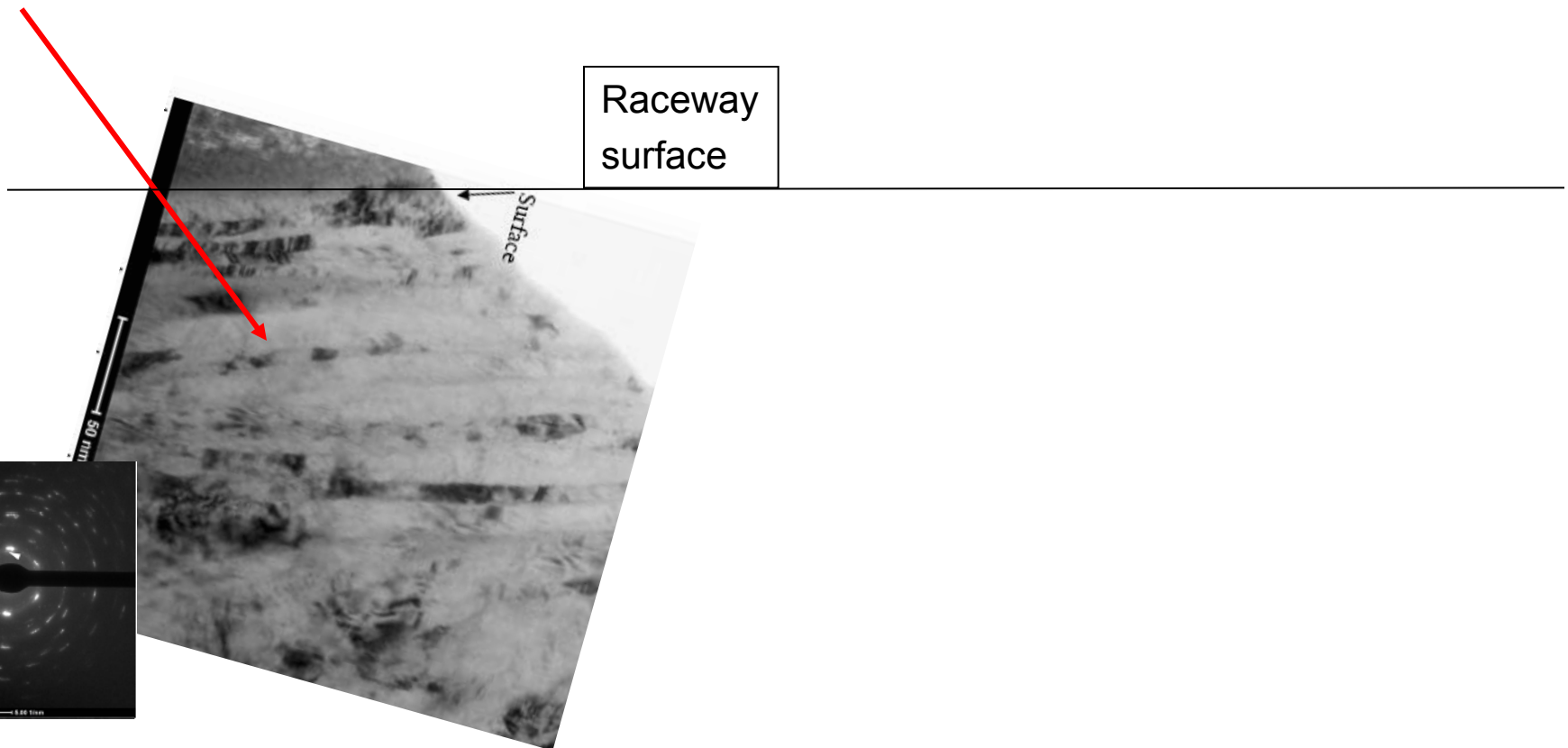
Comparison of raceway surface roughness

| Variant | Ra new raceway (μm) | | Ra loaded raceway (μm) | |
|------------------------------------|-------------------------------------|-------|--|-------|
| M Standard martensite | 0.090 | 0.009 | 0.055 | 0.003 |
| | $\Delta = 0.035$ | | | |
| HA Bearing assembly at 130 C | 0.092 | 0.007 | 0.079 | 0.011 |
| | $\Delta = 0.013$ | | | |

Hammering of HA raceway surface is **smaller** then standard martensite.

Why less hammering with a HA bearing ?

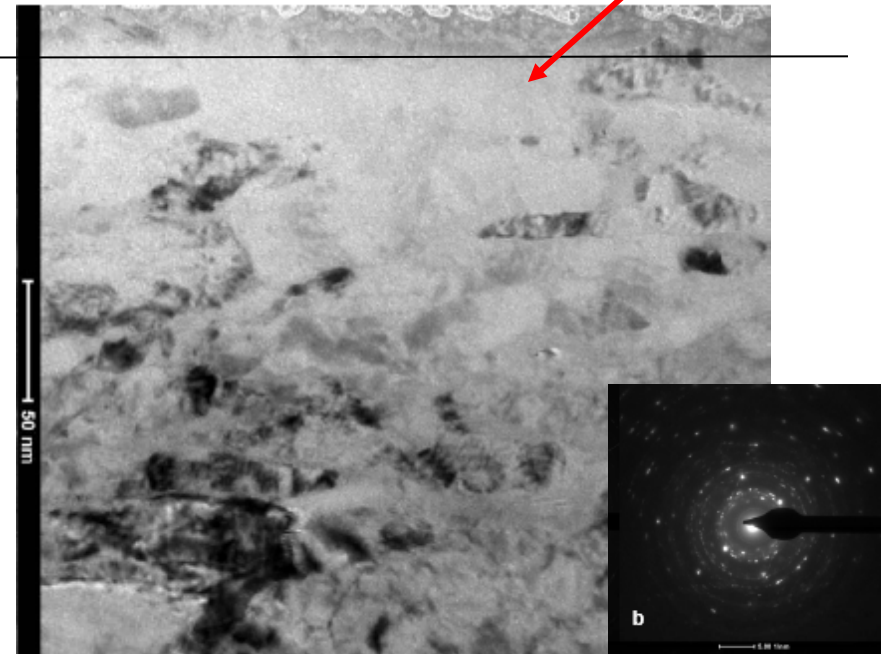
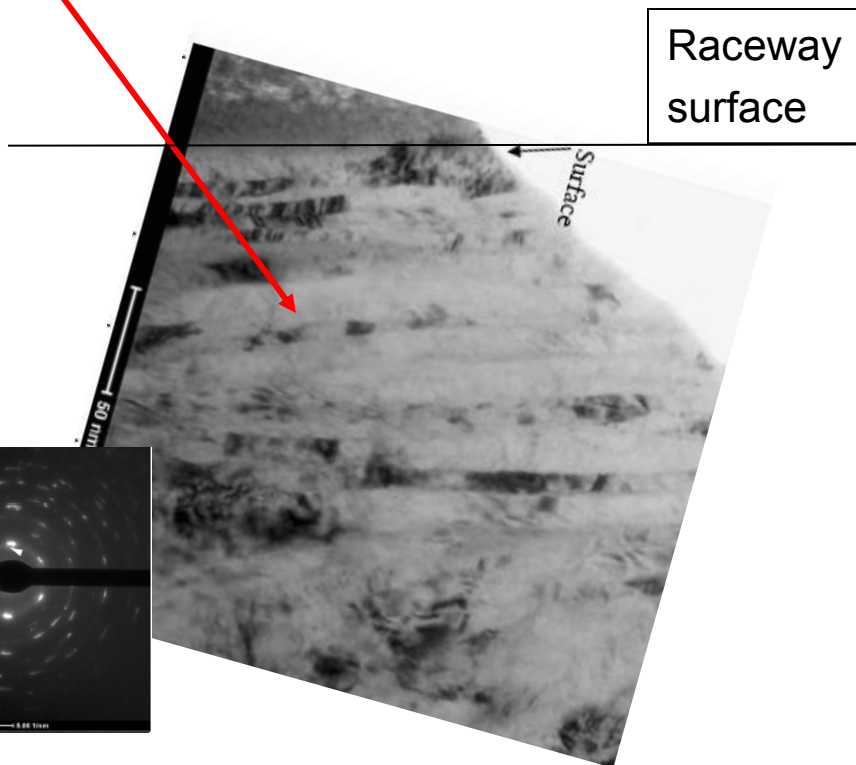
New bearing raceway surface \Rightarrow
100/200 nm layer of small lamellar
grains about 20/30 nm thick

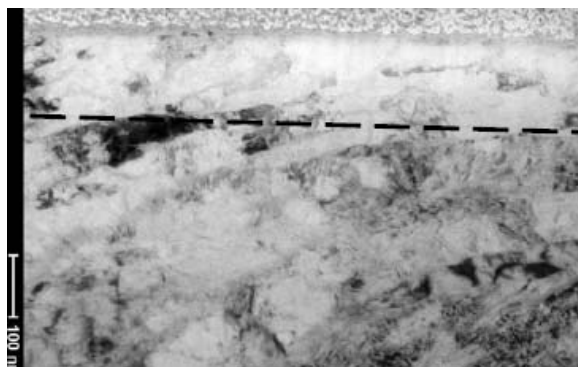
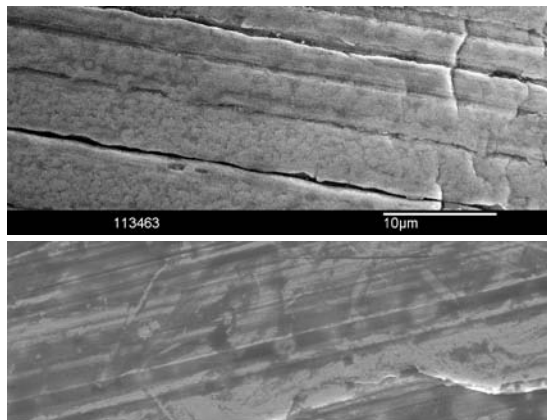


Why less hammering with a HA bearing ?

New bearing raceway surface \Rightarrow
100/200 nm layer of small lamellar
grains about 20/30 nm thick

After bearing assembly at 130 C
 \Rightarrow 100/150 nm **recrystallized layer**
at raceway surface with grains of
about 5/10 x 30/40 nm





Preventing drivers :

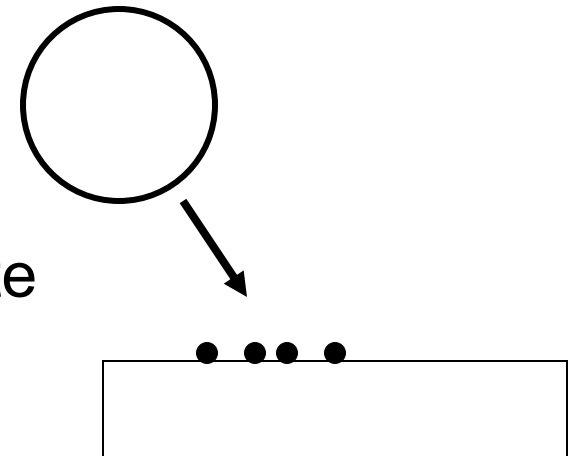
- "operation time" :
hammering = strain hardening ⇒ after some time
- "case carburised" :
retained austenite
- black oxidised :
oxide layer
- hot assembly :
recrystallized layer

**Common
factor =
raceway
wear
resistance**

▮ Is there a link between wear and generation of impact load ?

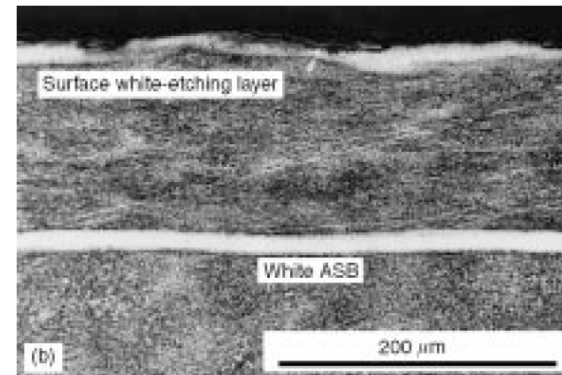
▮ Experiment :

- oblique ball **impact** on a steel plate
- quartz **particles** on the plate



Test result :

- subsurface adiabatic shear bands
= subsurface impact damage



B. Zhang,
Adiabatic
shear bands
in impact
wear

Conclusion :

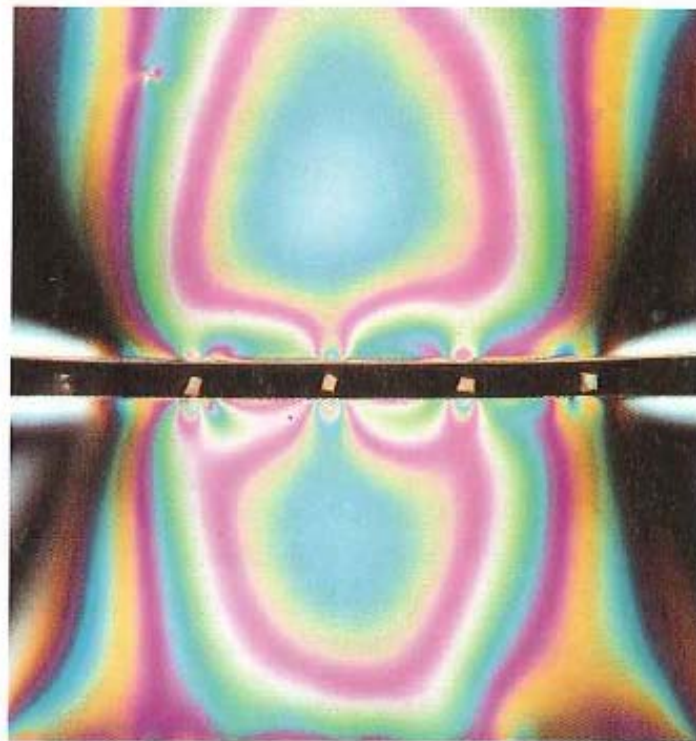
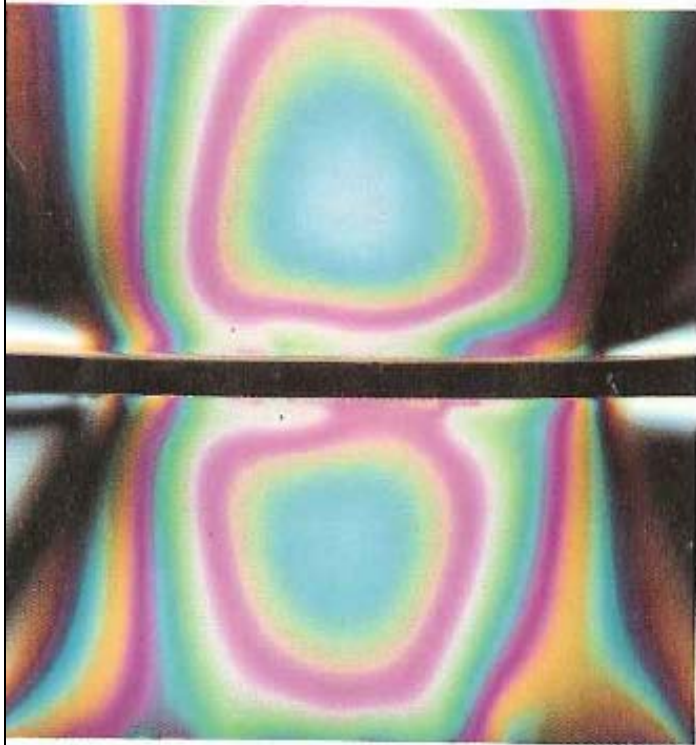
- load system of "ball drop + **particle**" ⇒ subsurface impact damage
- load system :
 - ball drop = limited impact load
 - **particle on the surface = impact load concentrator**

Particles in EHD contact under static load = stress risers

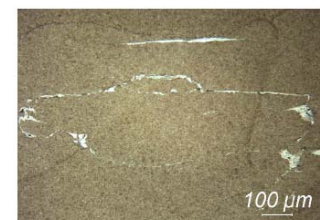
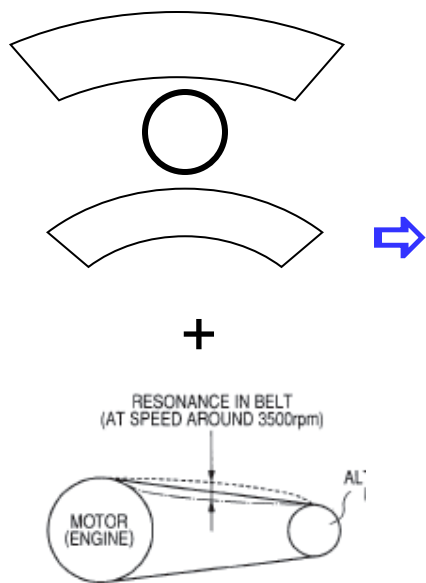
Fig 2 Optical interference patterns showing stress in a model of a rolling contact

a) clean surfaces completely separated by lubricant film

b) solid contaminant particles contained in the lubricant film



Wuttkowski,
Ioannides,
The effect of
contaminants
on bearing
life.



roller bearing
+
dynamic load
conditions
from application



what is the
missing link
in the chain
of events ?
IMPACT LOAD

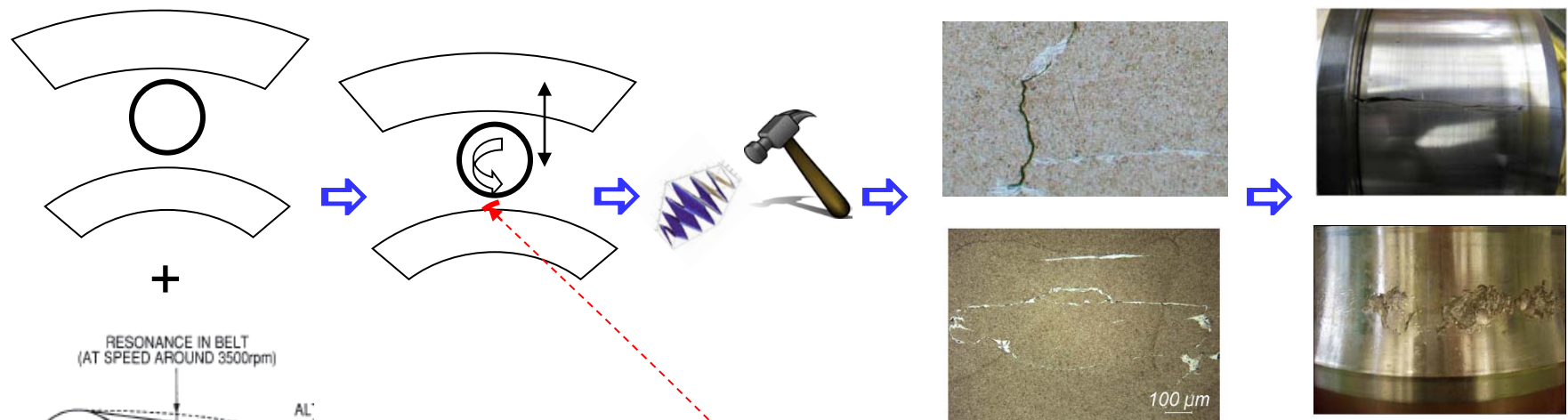


subsurface
impact
damage



WEC/irWEA
bearing
failure

5. Hypothesis development & Material research



roller bearing
+
dynamic load
conditions
from application



raceway hammering
& shear stress
= **hammering**
wear particle
+ rolling contact
⇒ **IMPACT LOAD**



subsurface
impact
damage



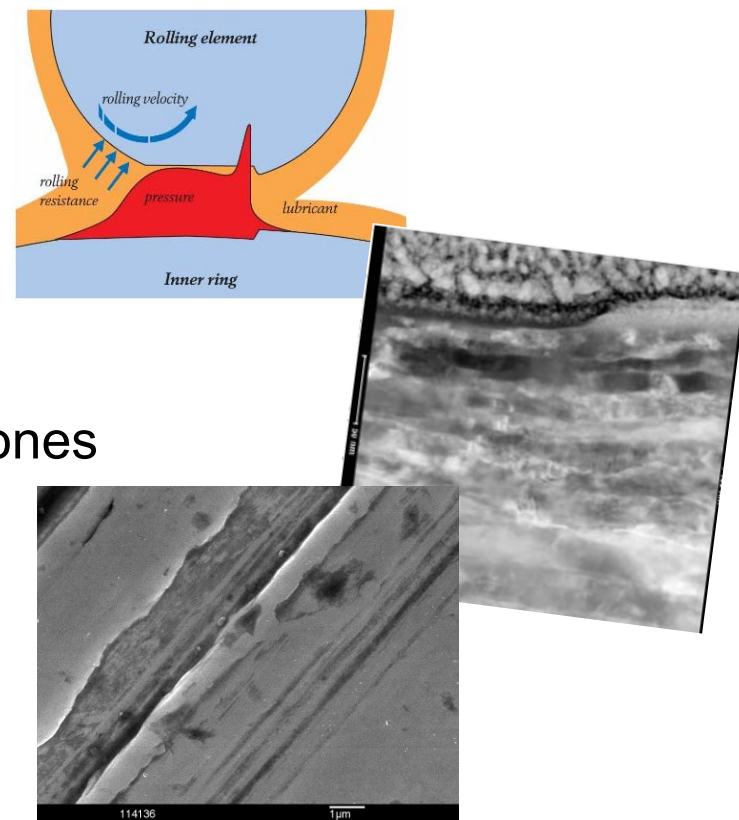
WEC/irWEA
bearing
failure

What is the mechanism behind raceway hammering ?

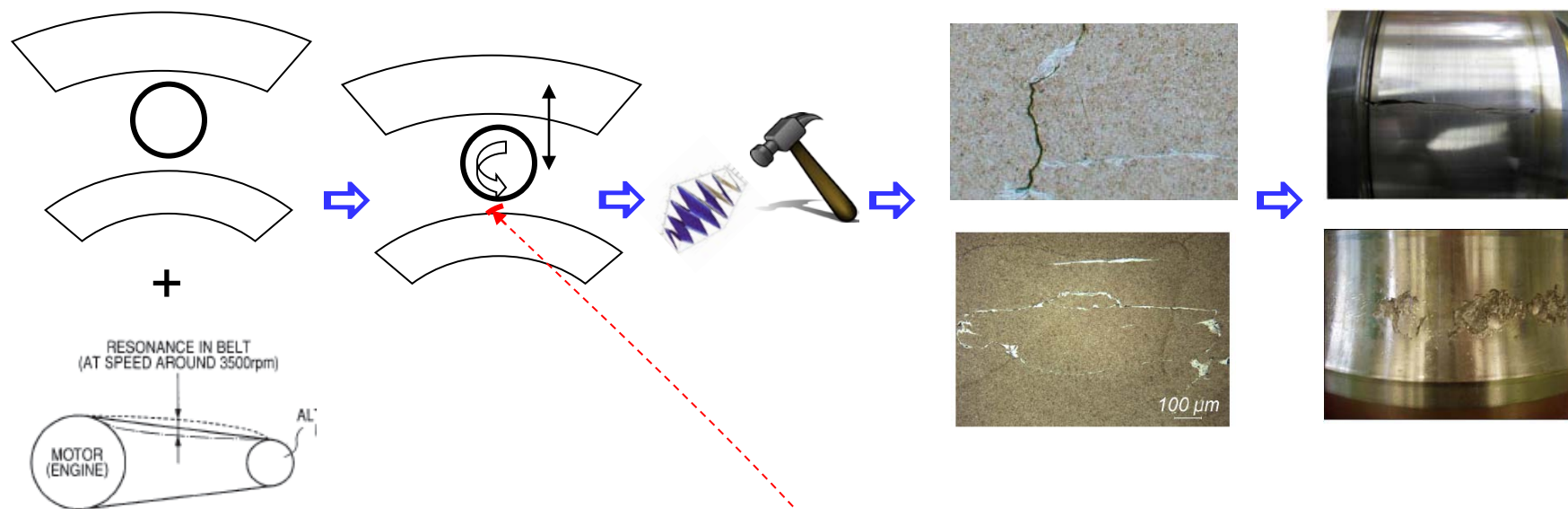
Possibilities :

- end of EHD pressure peak
- mixed friction
 - yes : hammering in dedicated load zones
 - no : no signs of material removal at the raceway surface
- . . .

Answer : to be investigated



5. Hypothesis development & Material research



roller bearing
+
dynamic load
conditions
from application

⇒ raceway hammering
& shear stress

= **hammering
wear particle**

+ rolling contact
⇒ IMPACT LOAD

⇒ subsurface
impact
damage

⇒ WEC/irWEA
bearing
failure

**Potential to enter via other
wear driving mechanisms**

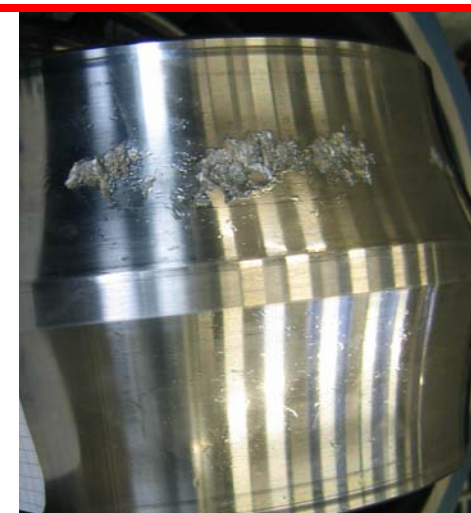
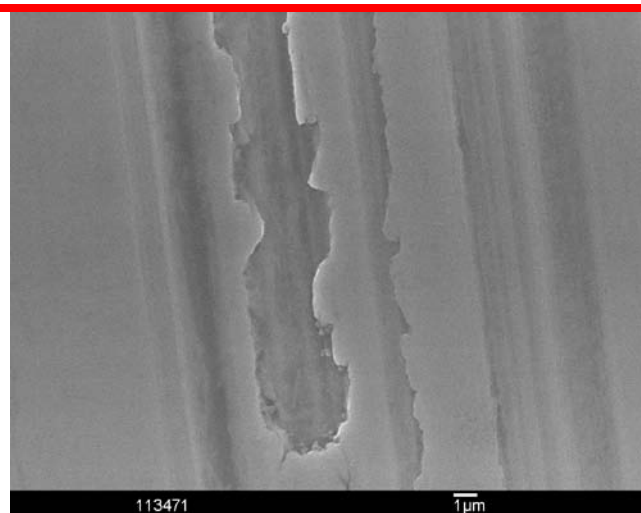
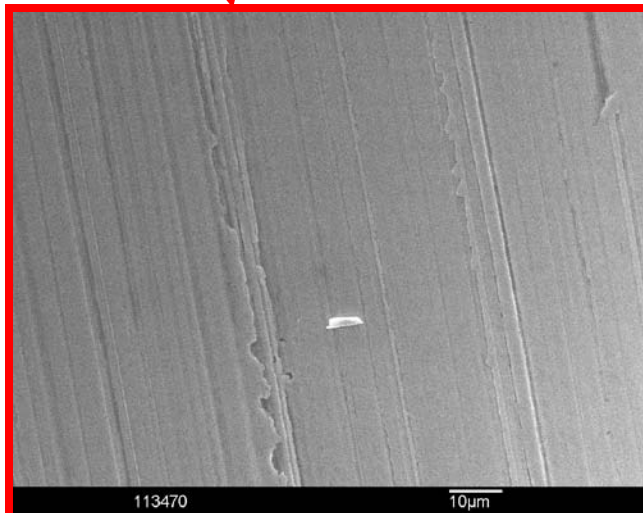
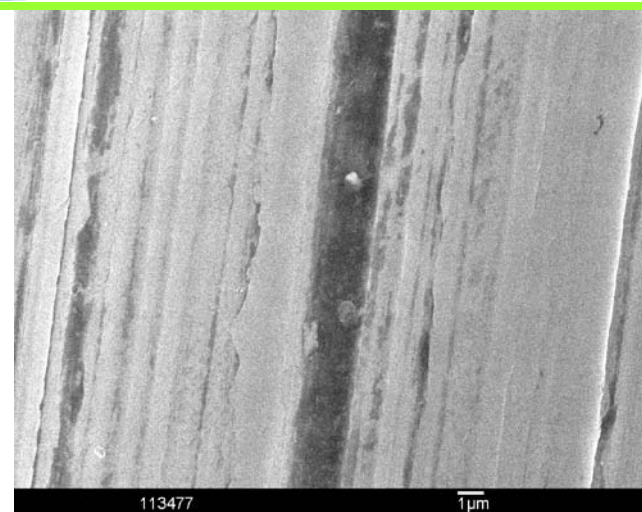
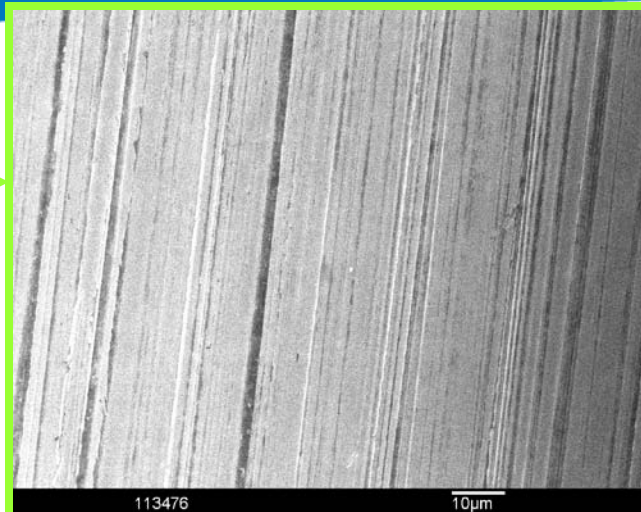
▮ Promoting the WEC/irWEA bearing failure mode :

- SRB and BB : internal slip
- big roller size :
 - higher mass
 - higher inertia \Rightarrow increased slip
- high dynamic bearing applications



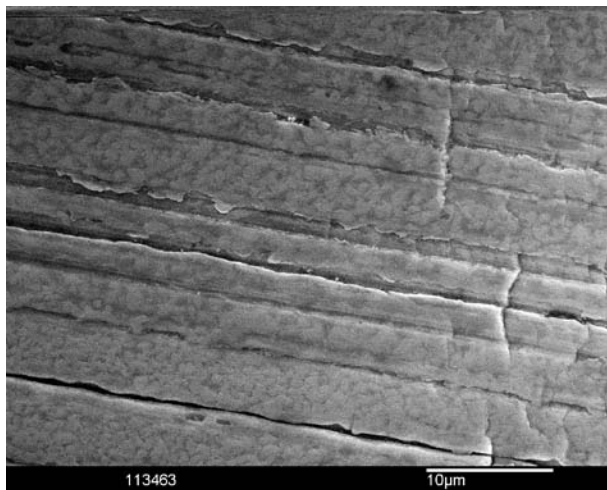
**Contributors
towards
hammering
wear and
shear stress**

5. Hypothesis development & Material research

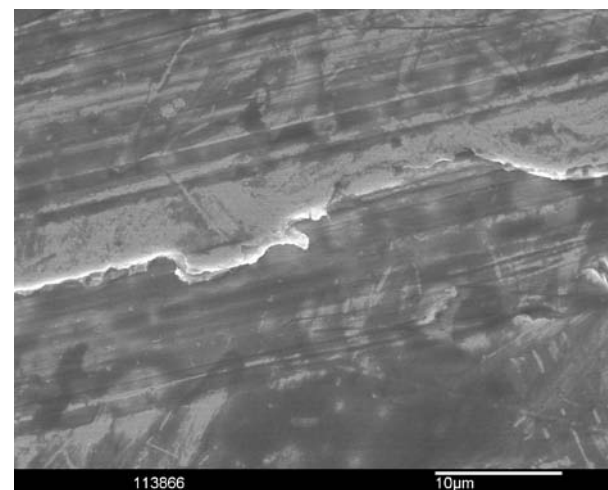


Raceway of inner ring SRB of WEC/irWEA critical bearing application (not failed). More intense hammering wear on sample 2 from middle of raceway where spalling is initiated in case of WEC/irWEA bearing failure.

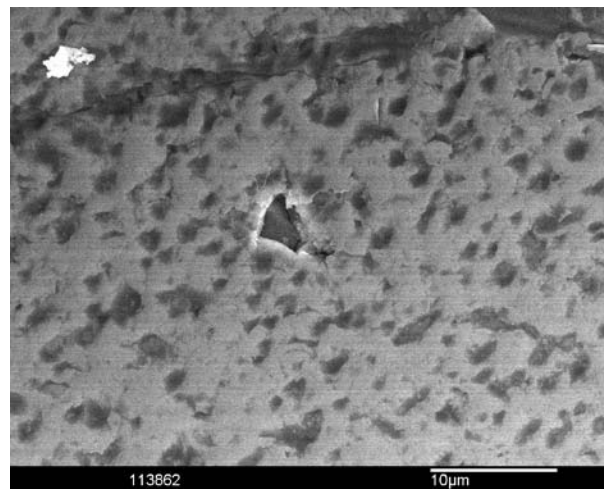
5. Hypothesis development & Material research



Raceway
martensite
bearing
supplier

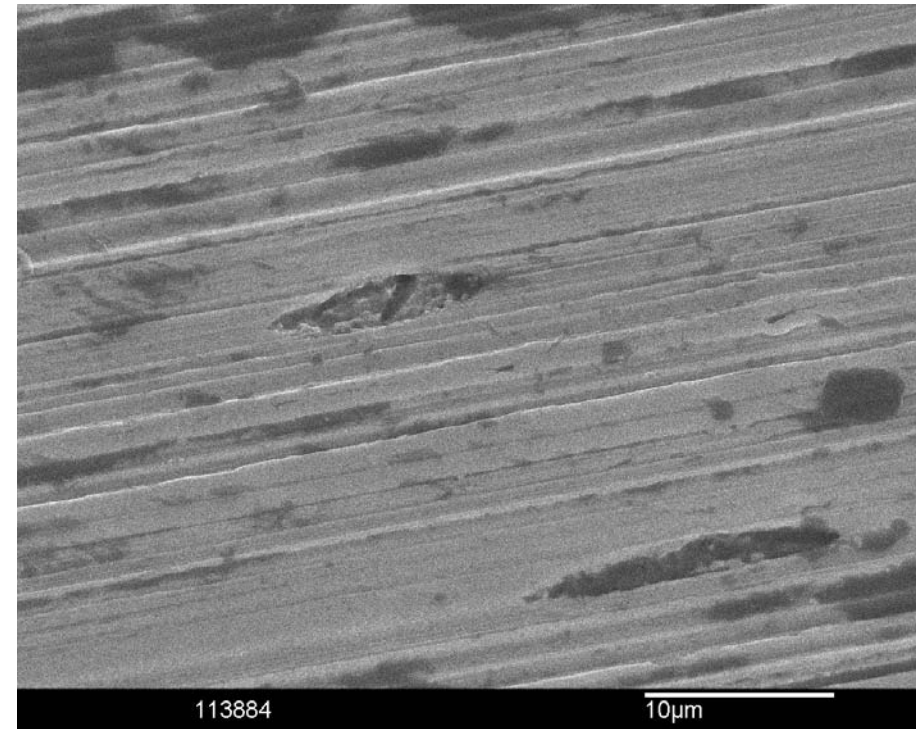
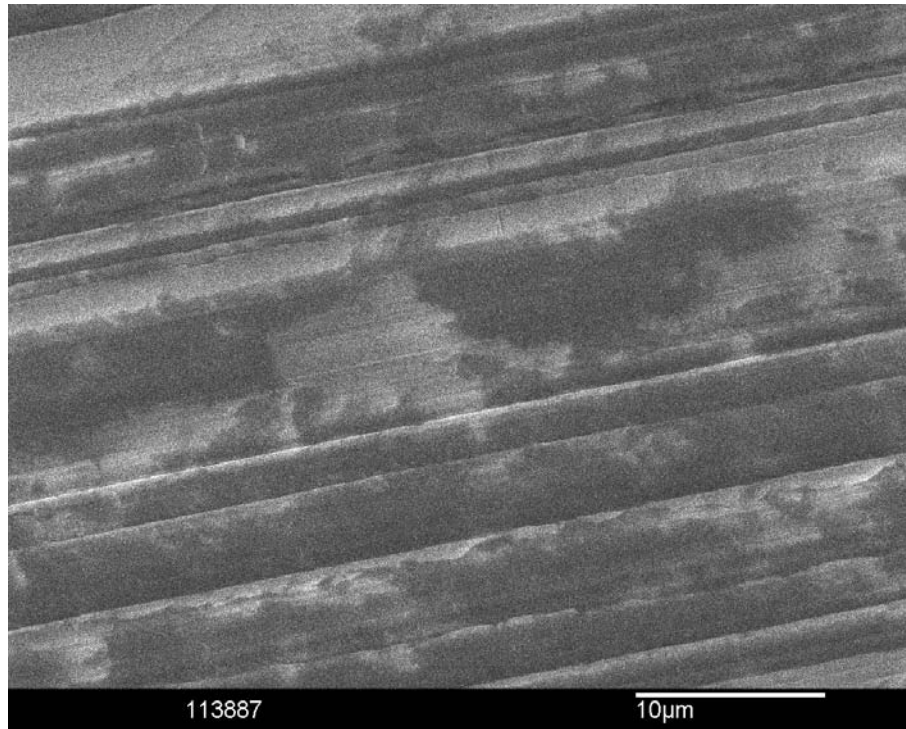


Raceway
case
carburised
bearing
supplier



Raceway
case
carburised
Hansen

Comparison between raceways. Lower picture is Hansen case carburised without hammering wear. No WEC/irWEA failures on Hansen case carburised raceways.



Hansen high speed gear tooth with limited (left) and more (right) wear development. Gear flank topography has minor hammering wear of asperities tops. No WEC/irWEA gear failures observed on Hansen gears.

Agenda

- 1. Introduction
- 2. Material observations in WEC/irWEA failed bearings
- 3. Interpretation of material observations
- 4. Hansen wind experience
- 5. Hypothesis development & Material research
- 6. Proposals for WEC/irWEA research
- 7. Summary and way forward

→ BACK TO BASICS.

→ What are the basic technology area's ?

→ Material damage in failed bearings ⇒ **IMPACT**

→ EHD contact ⇒ **TRIBOLOGY**

→ The identified counter measures are interpreted as surface treatments that increase the wear resistance ⇒ **WEAR** and **SURFACE TREATMENTS**

Impact :

- **simulate** impact load system (<http://www.ce.berkeley.edu/~shaofan/spall.html>) :
 - simulate material damage
 - determination of load system
 - hammering wear hypothesis
 - surface treatments
 - microstructures
 -
- **experimental**
 - conceptual test rig to simulate material failure mode :
 - ball impact
 - wet plate with different roughness values & coatings(see existing test rigs for coatings)
 - + high frequent (> 1 MHz) instrumentation

→ Tribology :

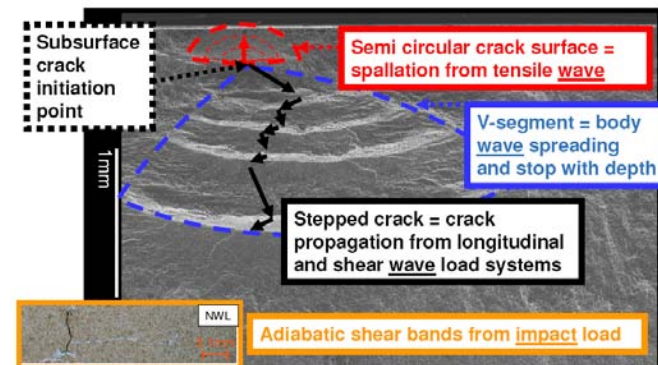
- **theoretical** work :
 - model micro EHD
- **experimental** work on **small** scale (fundamental research) :
 - measure pressure peaks :
 - roller element impact
 - flat wear particle on (coated) surface
 - contaminated oil
 - measure wear
 -
- **experimental** work on **large** scale (validation) :
 - large bearing test rig + dynamic load conditions
 - large gear unit test rig + dynamic load conditions

Agenda

- 1. Introduction
- 2. Material observations in WEC/irWEA failed bearings
- 3. Interpretation of material observations
- 4. Hansen wind experience
- 5. Hypothesis development & Material research
- 6. Proposals for WEC/irWEA research
- 7. Summary and way forward

7. Summary and way forward

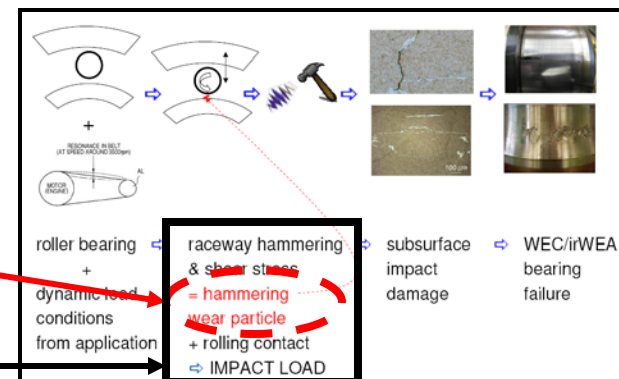
- Material observations in WEC/irWEA
 ⇒ bearing material failure mode =
subsurface impact damage



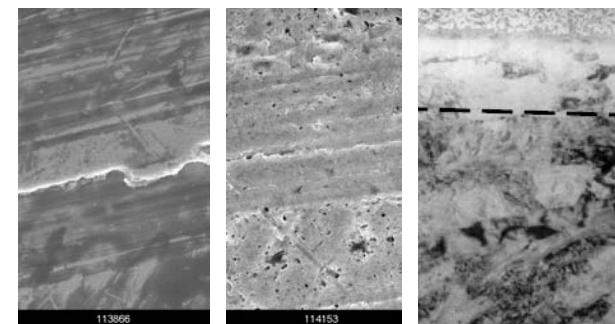
- The root cause hypothesis is reviewed

- hammering wear** is a link in the chain of events

- raceway wear particle + rolling contact =
IMPACT LOAD



- Increased raceway wear resistance** is common tribological system of the industrial solutions



7. Summary and way forward

↪ WEC/irWEA bearing failure mode in gear driven WTG :

- big size roller bearings + vibrations ⇒ **reliability risk**
- control the risk !

↪ Hansen strategy :

- **share** the know how in an early phase
- increase **confidence** in the gear driven WTG concept

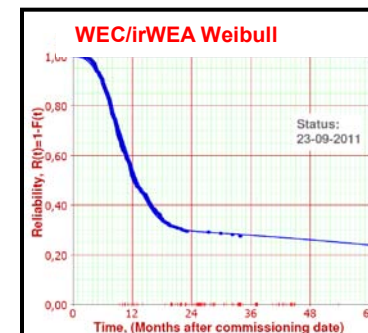
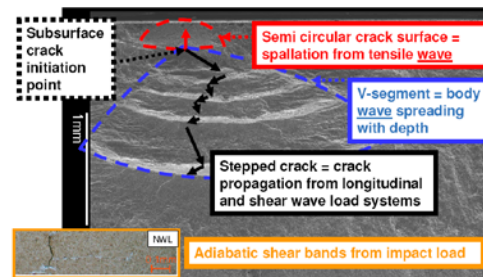
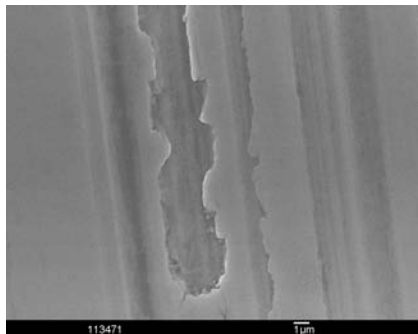
7. Summary and way forward

- ▮ The identified **robustness increasing measures** are :
- raceway surface treatment
 - black oxidised
 - recrystallized layer by Hansen hot assembly
 - case carburised microstructure
 - Hansen case carburised microstructure (zero WEC/irWEA failures)
 - inconsistency between bearing suppliers (preferred bearing supplier)
- ▮ Hansen is introducing **this** for new gearbox designs and serial production

7. Summary and way forward

Further research by **bearing suppliers** of the **new** impact fatigue failure mode on bearings :

- complete understanding
- cost effective solutions
- application dependant solutions



Hammering Wear Impact Fatigue Hypothesis

We believe that we can control the risk

Thank you for your attention

Questions ?

▢ "What can be effective as WEC/irWEA robust increasing counter measures ?" ⇔ "How can we avoid or reduce raceway wear ?"

- (reduce vibrations)
- **wear resistance raceway surface :**
 - recrystallized layer via Hansen hot assembly
 - strain hardening via shotpeening, rolling, . . .
 - hard coatings : nitrogen, . . .
 - . . .
- **wear resistance microstructures**
 - case carburised (reference towards Hansen and preferred supplier)
 - microstructures with austenite : nanostructured bainite, . . .
 - nitrogen charged microstructures
 - . . .
- **optimized EHD contact to avoid or limit wear :**
 - soft coatings :
 - black oxidised (stabilized wear conditions)
 - . . .
 - lubricant & oil film :
 - grease (sealed bearing)
 - additives (increased friction and or wear is a risk)
 - reduce raceway surface roughness
 - . . .

Apply the most
cost effective
solution